Froth Washing in Flotation

Subjects: Mining & Mineral Processing
Contributor: Tawona Martin Jera, Clayton Bhondayi

Froth flotation is a mineral processing technique that is popular when processing low-grade ores. It involves introducing chemically treated, finely ground ore in the form of a slurry into a flotation cell where the air is also added in the form of bubbles. The cell is agitated resulting in the air bubbles rising to the top and creating a froth, as bubbles rise, hydrophilic particles attach to the rising bubbles creating a froth which is collected in the weir or using launders for further treatment. The froth is washed using various froth-washing techniques to reduce entrainment and improve the grade of the froth. Froth washing can be achieved using froth washing jets or froth washing trays, this can be achieved internally/externally with regards to the position in the froth layer.

Keywords: froth washing ; entrainment ; wash water ; froth stability

1. Introduction

Froth flotation is a mineral processing technique that is popular when processing low-grade ores. It involves introducing chemically treated, finely ground ore in the form of a slurry into a flotation cell where air is also added in the form of bubbles. The chemicals added to the slurry manipulate the surface of valuable minerals by rendering them hydrophobic, while gangue particles remain hydrophilic or vice versa in reverse flotation where the gangue is floated and the valuable mineral is rendered hydrophilic [1]. In the pulp phase of the flotation cell, air in the form of bubbles of a specific size pick up the hydrophobic particles and rise to the top, where they form a froth that increases in height as more bubbles impinge at the bottom; it eventually overflows the concentrate weir and is collected in launders.

The performance of the froth phase is governed by sub-processes, namely liquid drainage, particle detachment or attachment, and bubble coalescence and break-up. These sub-processes dictate froth recovery and grade, which are typically used as performance measures of the froth [2]. Froth recovery is defined as the fraction of particles that enter the froth phase, survive its cleaning action and are recovered as the concentrate [3]. Grade refers to the content of the marketable product in the concentrate expressed as a percentage of the total concentrate [3]. The grade of the concentrate is lowered by entrainment, which is a non-selective process responsible for carrying fine particles from the pulp into the froth. Particles are entrained into the froth by the liquid that is pushed into the froth in the bubble wake or by mechanical means through turbulence and slime coatings [4][5]. Mechanisms to explain entrainment that have been established in the literature include: the Moys [6] theory that states that unattached particles are carried upwards in bubble lamella; the Yianatos et al. [7] model that indicates that particles are transported to the froth in the wake of ascending air bubbles. Smith and Warren [8] used the bubble swarm theory to suggest that water in the pulp phase is mechanically pushed into the froth phase by a rising swarm of bubbles. The water carries with it fine particles, the bulk of which are gangue minerals, because there is a high concentration in the pulp. Gangue minerals can also be recovered through entrapment [9].

1.1. Froth Washing

This is another method that can be used to “clean” the froth off entrained particles. Froth washing is effective in reducing the number of entrained particles in the froth [10][11][12][13][14][15][16]. The process of froth washing involves spraying water onto the froth. The added water helps the drainage of the entrained/loosely held particles back into the pulp phase by displacing the entrained liquid that transmits gangue particles. Froth washing increases grade, flotation recovery, froth stability and mobility, and thus enhances the performance of a flotation cell [11]. Despite the success achieved with froth washing, especially in column flotation cells, the Jameson cell (particularly in the coal processing industry), there are factors that lead to sub-optimal performance if they are not optimised. These include wash-water flowrate [10][11][17][18]; wash-water quality [10][11][12][13][14][15][16]; type and mechanism of wash-water delivery/distribution [11][12][13][15][16][19][20][21][22][23]; area covered by wash water [10][11][12][13][24][25]. Maldistribution of wash water [11][25][26] affects the degree of froth mixing, causes channeling and short-circuiting in froth [27], and can result in suboptimal metallurgical performance of a flotation cell. An excessive number of fine particles in the pulp may increases entrainment, and froth washing has been used to counter this extra entrainment [5][10][11][12][13][14][15][16].

2. Froth Phase Sub-Processes

In froth flotation, the particles of interest are physically separated from the gangue minerals by taking advantage of their ability to adhere to the surface of bubbles, due to particle surface hydrophobicity. The hydrophobic particles attach to the air bubbles and are carried to the surface, where they form a froth, while hydrophilic particles remain in the pulp to be drained as tails [28]. Initially, the loaded bubbles entering the froth are mostly spherical, with a liquid film surrounding them. However, as more bubbles impinge at the base of the froth, the layer of froth increases in height and slurry drains back into the froth. The liquid around the bubbles (bubble lamella) drains and becomes increasingly thinner, which encourages bubble coalescence. The bubbles thus become larger and polyhedral in shape, with plateau borders forming at the junction of three bubbles [29], i.e., tubular conduits in which water and detached particles flow. Detached particles may reattach to the available surface of rising bubbles or drop and drain back to the pulp phase. Thus, the froth phase sub-processes, bubble coalescence, particle detachment and reattachment, and froth drainage significantly influence the overall grade and recovery of the froth [1][30]. Froth phase sub-processes dictate the type and composition of particles in the lamella and plateau borders at any given time [29]. When two bubbles collide and merge, oscillations due to this collision result in the loss of particles [31][32][33]. Therefore, coalescence results in the detachment of particles. The detached particles can reattach to the rising bubbles via a selective process, based on hydrophobicity and particle size [1][6][34], which influences overall flotation performance.

2.1. Brief Overview of Froth Behavior

The major function of the froth is to transport the valuable minerals to the concentrate weir or froth discharge launders. Therefore, the froth should be able to resist bubble coalescence and bursting events, a property that is defined as froth stability. Several factors influence froth stability, including particle size and hydrophobicity [2][35], quality of process water, gas dispersion characteristics, particle contact angle, temperature, salt concentration, etc. [36]. Farrokhpay [36] reported that froth stability plays an important role in determining grade and mineral recovery. The froth should be stable enough to allow drainage of gangue particles and recovery of mineral values. A froth that is too stable is difficult to manage and leads to difficulties in mineral recovery because it has a high mineral content, which retards drainage of hydrophobic particles to the launder [37]. If the froth is unstable (i.e., breaks continuously as the liquid drains from between bubbles) [37], it results in low recovery because mineral-laden bubbles collapse before they are transported over the concentrate weir. Unstable froths are runny and consist of loosely packed spherical bubbles with little valuable minerals. A very stable froth i.e., metastable froth is sticky with a high froth load due to closely packed ellipsoidal bubbles. Very stable froths are too viscous and have large bubbles entraining a large number of gangue minerals, which consequently leads to a poor grade of concentrate [37].

Very stable froths become dry in the upper layers [38][39] as a result of particles dropping back and liquid drainage. Wash water sprayed compensates for the water lost in the upper layers of the froth preventing bubbles from bursting events, thus increasing froth stability and improving the recovery of particles [11][38][39].

In addition to being of acceptable stability, the froth should also be mobile, in order for it to flow to the concentrate launder. A froth property called froth mobility refers to the flow streamlines that occur in the froth between the pulp-froth interface and the froth discharge [40][41]. Froth mobility has been linked to the froth structure. Moolman et al. [37] stated that large elliptical bubbles with high froth loading are a result of an excessively stable, sticky froth. The characteristics of a sticky froth are high viscosity with lower mobility compared to that of an ideal froth. A runny froth is too watery, has low mineralisation and is excessively mobile [37]. An ideal froth is not too runny or too viscous.

Froth rheology is an important froth property in flotation because it has the possibility of affecting both froth mobility and froth stability [42]. One of the terms associated with froth rheology is viscosity. Experienced plant operators have often used their fingers to test whether the froth is viscous so that operating variables can be adjusted promptly. Shi and Zheng [42] reported that the froth becomes drier and more viscous when it stays longer in the flotation cell on its way to the launders. This can only be attributed to water draining from the froth. As a result, water and entrained particles per unit volume of froth decrease. In the process, froth mobility is lowered. Froth washing has the benefit of compensating for the water lost in the upper layers of the froth, which improves froth mobility, stability and recovery [11][38][39]. Therefore, froth washing influences froth rheology. Shi and Zheng [42] reported that the froth becomes less viscous as the water hold-up in the froth increases. No other research has been conducted on the impact of froth washing on froth rheology. Kaya [11] reported that wash water reduces bubble coalescence, which leads to improved recovery in flotation. After introducing wash water, the bubble lamella thickens. The number of large particles held in the froth increases. In addition, the amount of water draining from the froth also increases and effectively "washes' down entrained particles; this is effectively a secondary concentration process which leads to an improved froth grade. The increase in the recovery of coarse particles and the secondary concentration process results in an increase in recovery and grade [11].

2.2. Transporting Gangue Minerals into the Froth

Three main mechanisms have been identified as being responsible for transporting gangue minerals into the froth and these are entrainment, recovery as composite particles using their hydrophobic portion attached to bubbles and entrapment by aggregates attached to bubbles [8]. Entrainment is known to be the biggest contributor to recovering gangue minerals in the froth [8][9][43][44][45][46][47][48][49][50]. It is a process that transfers fine particles into the froth through mechanical means [51][52]. The process is non-selective; therefore, fine particles of both valuable minerals and gangue minerals are transported into the froth. However, because gangue minerals are typically abundant compared to valuable minerals, a reduction in concentrate grade is observed. Therefore, entrainment must be managed actively.

Entrainment is known to take place in two steps. Step 1 involves moving particles from the top of the pulp, across the pulp-froth interface and into the froth. Step 2 involves transferring these particles from the froth phase to the concentrate [47][48][50]. Generally, three mechanisms are considered responsible for Step 1. These are: (i) unattached particles being carried upwards in bubble lamella, which is known as the boundary layer theory [6][9][44][45][53]; (ii) the bubble swarm theory [8][49], which posits that swarms of bubbles below the pulp-froth interface mechanically push water and suspended particles across the pulp-froth interface; (iii) the bubble wake theory [46][53], which posits that the bubble wake transfers particles into the froth. Water in bubble lamella, or in the wake of a bubble or water being mechanically pushed by swarms of bubbles is central to explaining entrainment. Thus, several relationships between water recovery and particle recovery by entrainment have been suggested, including the dominant linear relationship, as observed by several researchers [4][6][8][21][39][53][54][55][56][57][58][59][60].

Another mechanism for transporting gangue into the froth was suggested by Gaudin [9] as reported by Smith and Warren [8], i.e., entrapment. Entrapment takes place when non-floatable particles (gangue minerals) are trapped between valuable particles that are attached to adjoining/clustered bubbles and which are recovered to the froth product [9][11]. This lowers the grade of the froth. Zheng et al. [55] further reported that entrapment occurs when the thickness of the froth lamellae and plateau borders reduces to a value similar to or less than the particle size, hindering the free drainage of particles. Zheng et al. [55] further stated that entrapment can be responsible for the disproportionately higher recovery of larger particles of gangue minerals relative to fine particles. Kaya [11] further reported that entrapment becomes more dominant with low water recovery or when the froth becomes dry. Introducing froth washing was found to reduce entrapment.

2.3. Managing Entrainment Recovery

Several factors are known to influence entrainment, including feed properties, mainly particle size and density [8][53][61][62][63][64]; operational parameters, such as pulp density [55][64], impeller speed [53][65], gas rate [53][55] and froth height [6][53][54][55][66][67][68][69]. Controlling and manipulating these factors is one way of managing entrainment. Fundamentally, the reduction in particles recovered by entrainment targets the two-step process that results in the entrainment of particles. For instance, Zheng et al. [55] observed that the degree of entrainment increases with an increase in the air rate and decreases with an increase in the froth height. An increase in air rate leads to an increase in the rising velocity of the froth and shortens froth-retention time. Therefore, a lower proportion of particles per unit mass of water drains back into the pulp from the froth phase. Increasing the froth height prolongs the froth-retention time, which allows more water and unwanted fine particles to drop back into the pulp. This produces a cleaner froth [55]. In this case, manipulating the gas rate or froth height means targeting Step 2 of the entrainment process, by providing conditions that reduce the recovery or transport of entrained particles to the concentrate launder. Cilek [70] noted that, in mechanical cells, the impeller speed can be regulated to a range within which the recovery of gangue minerals by entrainment would be reduced but true flotation would be promoted. Akdemir and Sönmez [65] investigated the effect of the impeller speed on coal and ash recovery and entrainment. The results indicated an increase in recovery by entrainment as a result of increased impeller speed. In general, excessive agitation leads to an increase in the recovery of fine gangue particles. Control of agitation speed is primarily aimed at reducing Step 1 of the entrainment process, i.e., reducing transportation of unattached particles across the pulp-froth interface.

Froth-flow modifiers can also be used to control entrainment recovery by targeting the second step of entrainment. This is achieved through manipulating the froth-retention time. Altering the froth retention impacts the froth drainage and thus the entrainment recovery. Moys [43] and Bhondayi [71] studied the impact of a froth baffle on froth performance. In general, they found that a froth baffle leads to a reduction in entrainment, as the froth baffle elongates the path taken by the bubbles, thus increasing the time for draining the gangue particles. Therefore, baffles increase the froth-retention time for bubbles that enter the froth phase close to the concentrate weir, which improves the concentrate grade. Other froth-flow modifiers, e.g., crowders and launders, can also be used to manipulate the froth-retention time, and result in varying degrees of entrainment control.

Industrially, entrainment has traditionally been minimised by using multiple stages of cleaner flotation cells [72]. Column flotation became the preferred alternative to multi-stage cleaning for the coal industry [12]. Column flotation cells utilise froth washing. Froth washing involves introducing clean wash water within the froth or externally on top of the froth. The added clean wash water creates a net downward flow of water in the froth, which flushes out gangue particles and reduces the fraction of gangue minerals [10][11][12][13][15][16]. Thus, froth washing targets the second step of entrainment.

2.4. Froth Washing

According to Klassen and Mokrousov [24], froth washing was first applied in the flotation of coal and resulted in improvements in coal recovery. Wash water is uniformly sprinkled on the whole froth surface in all flotation columns or at the overflow lip in mechanical cells. Kaya [11] suggested that wash-water flow rates should be maintained between 7% and 12% of water in the flotation cell feed. Frothing agents at the same concentration as in the flotation cell feed may be added to the wash water to stabilise the froth [10][13][73].

Column flotation cells are common in coal flotation or applications where a deeper froth is required [15]. Wash water is also sometimes applied in mechanical flotation cells, although this is not very common; however, the water requirement is lower, mainly because these cells are operated at a lower froth height compared to column flotation cells. Compared to mechanical cells, huge success has been realised using froth washing in both column flotation [74] and Jameson cells [75], lowering entrainment and improving the grade of the concentrate. Column and Jameson cells have froth-washing systems to ensure that the entire froth surface is washed, while mechanical cells utilise washing at the cell lip [15]. Froth washing is also widely used in cleaner stages of flotation cells [12][76][77]. However, little application has been reported in scavenger cells, which contain the largest amounts of gangue particles compared to floatable material [15]. Scavenger cells are susceptible to entrainment due to shallow froth depth and less stable froth, which contains slow floatable minerals [12].

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