CHAPTER 7.4

Froth Management

Jason Heath and Kym Runge

ROLE OF FROTH IN FLOTATION CELLS

When air is released below the surface of a fluid, it will naturally want to move to the region of lowest pressure, usually the surface. An analogy is the rising of air in a freshly poured beer to form a frothy head. In the industrial process of froth flotation, air is added below the surface of a liquid–solid mixture and the air also rises to the surface of the vessel. However, in froth flotation the goal is for targeted hydrophobic mineral particles to be attached to and carried by the air bubbles to the surface. The buoyancy of the air–particle aggregates results in the accumulation of air, solid particles, and water in a low-density, three-phase mixture at the top of the cell. This layer is referred to as the froth phase or simply "the froth," and is the uppermost region in a typical flotation cell (Gorain et al. 2000). A flotation reagent known as frother is usually added to the process to stabilize bubbles formed in the flotation cell and also the froth phase itself.

The froth is usually visible from the top of a flotation cell and often used by flotation operators as a first indicator of cell performance. As hydrophobic particles tend to accumulate in the froth, they give it characteristics and properties that the operator can observe with the naked eye or determine with the use of a simple device such as a vanning plaque. Before the introduction of continuous online slurry analysis instruments, the ability to read the froth was a hallmark of a good flotation operator.

Several decades ago, experts acknowledged that there is a separation of both the slurry and froth regions in a flotation cell (Harris 1976), and the performance of each of these contributes to the overall cell performance. One of the key functions of the froth is to provide an environment for mineral-laden bubbles to accumulate and stabilize when they reach the pulp–air interface. Figure 1 shows a typical flotation cell froth structure, with new bubbles reaching the lower edge of the froth from the slurry below, interstitial water visible between the bubbles, and the uppermost bubbles being larger because of bubble coalescence.

To be effective in concentrating the targeted minerals, the froth must have sufficient stability to carry the floated particles until they can overflow the launder lip and be removed from the cell. Although not drawn in Figure 1, the launder lip would typically be configured to allow the uppermost portion of froth to overflow the lip, enabling continual removal of froth from the flotation cell.

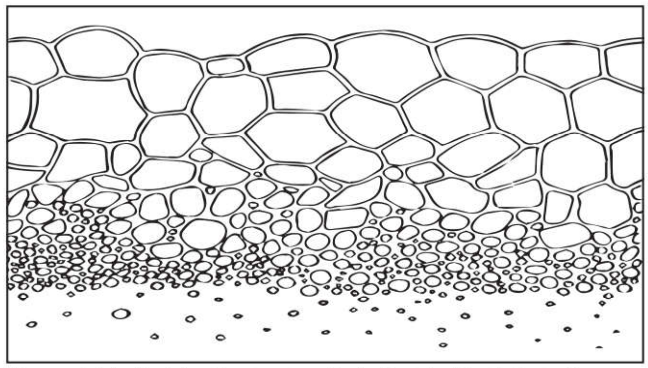

Figure 1 Typical froth structure in industrial froth flotation

The uppermost froth surface is normally where there is the highest concentration difference between the target hydrophobic minerals and other gangue minerals. This is due to the process of bubble coalescence and redistribution of the released particles. Bubble coalescence results in the release of the attached mineral particle load and interstitial water to the surrounding bubble surface, and the released particles must redistribute and compete for the remaining available bubble surface sites (Kaya and Laplante 1990; Barbian et al. 2005). This process of competition means that the most hydrophobically and physically suited (i.e., most energetically favorable) particles are then able to reestablish a bubble surface site, resulting in the rejection of less hydrophobic particles, which are typically lower in the target mineral and more hydrophilic. There is also a chance that, when no suitable bubble site is available, a hydrophobic particle will drop back into the bulk slurry phase. This is normally undesirable and is known as "particle drop-back."

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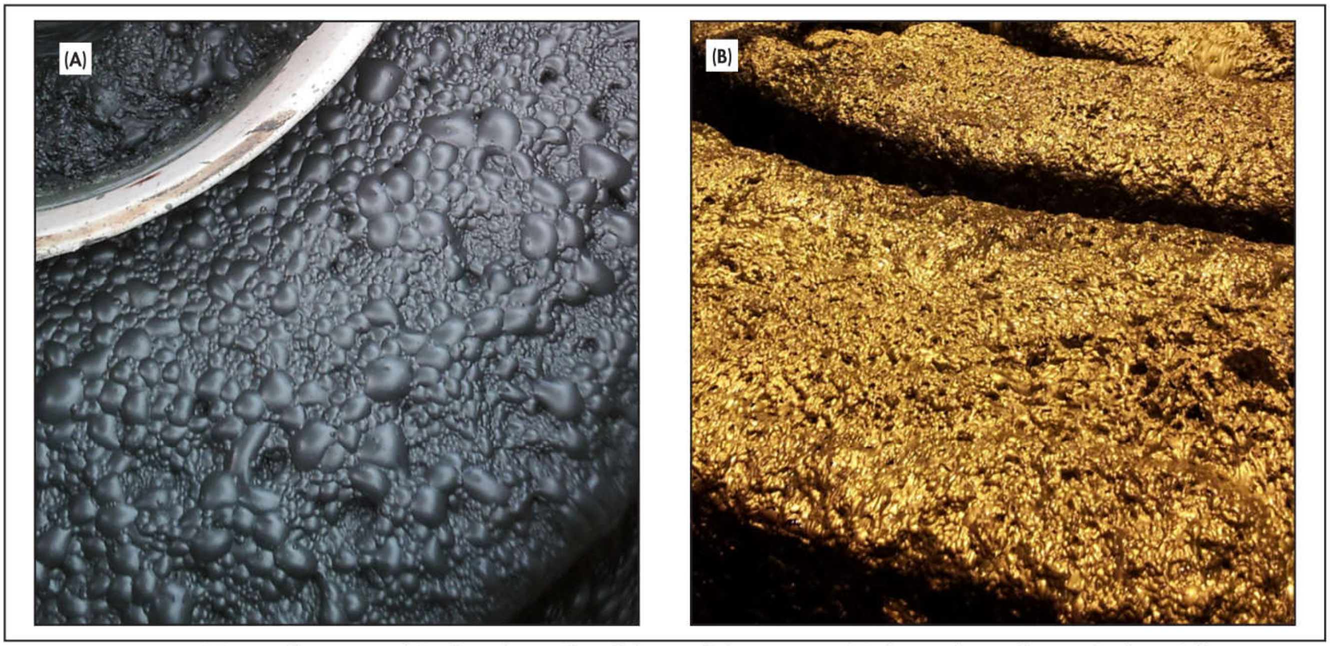


Figure 2 Compare (A) a well-structured froth with good mobility and drainage to (B) the "tight" or heavy froth with low mobility and static appearance

Aside from transportation of mineral particles, another important function of the froth phase is enabling selectivity of target minerals over entrained gangue. Suspended gangue particles in the upper regions of the pulp phase become trapped between the bubbles as they congest at the pulp–froth interface and are dragged upward into the froth. A well-stabilized and constructed froth provides drainage of interstitial water, taking with it any entrained hydrophilic gangue. The drainage of particles is strongly affected by the structure of the froth; for example, a "tight" froth composed of many small bubbles will have lower gangue drainage rates compared to froth composed of larger bubbles or of a mixture of bubble sizes including large bubbles (Ata et al. 2003). Additionally, the minimal bubble coalescence in a "tight" froth will further limit the difference in concentration between the lower and upper regions in the froth. An example of both of these froth types is shown in Figure 2.

The depth of the froth has a direct influence over the mineral concentration gradient seen from the bottom of the froth to the froth surface. Generally, with a deeper froth the average particle residence time in the froth is increased, which tends to increase the product grade. At the same time in a deep froth, particle recovery is usually decreased because of drop-back and other factors, negatively affecting recovery. These outcomes can be understood when considering the bubble coalescence and froth drainage principles as discussed previously in this chapter and in other publications (Ventura-Medina et al. 2003; Neethling and Cilliers 2003). Hence it is critical for a metallurgist to realize that froth depth is normally a very important parameter in optimizing flotation cell performance.

Consequently, without a suitably stable and well-constructed froth, no matter what froth depth is used, there will be poor froth recovery and transportation of attached mineral particles over the launder lip into the collection launder. This will generally result in overall poor performance of the flotation cell. Bubble coalescence in a froth is mainly a consequence of the rupture of thin liquid films, which occurs when the liquid content falls below a critical value. The particles in a flotation froth are largely responsible for producing the stable froth required for successful flotation, as they provide rigidity and impede water drainage. This property of particles in froth phases has been known for decades to play an important role (Lovell 1976) and was recently researched as part of the AMIRA P9 body of work (Achaye et al. 2015). The greater the amount of particles on the surface, the greater the froth stability, which is why flotation froths at the head of a flotation bank are significantly more stable than those farther down the bank where there are less hydrophobic particles reporting to the concentrate. Fine particles more densely pack on bubble surfaces than coarse particles, and this results in significantly higher bubble stability. Flotation performed with very little fines in the feed results in brittle froth and low froth recoveries (Rahman et al. 2012). Froth stability is optimum with moderately hydrophobic particles; highly hydrophobic particles were found to destabilize the froth in the work of Ata (2012).

Another important parameter of a froth is its mobility. Froth viscosity directly affects its mobility at the cell surface; a more viscous froth is less likely to move horizontally to the launder lip, resulting in a higher froth residence time and greater probability of froth collapse. Heavily laden dry froths with a small bubble size resist the flow of bubble over bubble that occurs as the froth moves toward the cell lip, resulting in a viscous immobile froth (Li et al. 2016). The froth mobility can be modified by changing the superficial gas rate and/or reagent concentrations, as these parameters affect the amount of water contained in the froth and modify the amount of particles present on bubble surfaces. For this reason, the use of depressants that minimize recovery of talcs or other gangue species can increase froth mobility and recoveries from a flotation cell.

Froth is also strongly affected by the type and concentration of frother, other reagents, and the process water quality, including the concentration of dissolved cations (Farrokhpay and Zanin 2012). These variables play a role in stabilizing the froth as well as affecting the amount of water drawn into the froth phase, which affects its mobility. The type of flotation cell, including the available froth surface area and transport distances, also play a role. For example, in larger flotation cells (i.e., greater than 100 m^3), it is widely accepted that a slightly stronger frother than normal will give better performance because of the typically larger transport distances involved with larger cells. Therefore, it is important for a metallurgist to adequately consider these points when looking to optimize flotation cell performance.

Particular attention to the froth-phase conditions is required when processing relatively coarse particles (>100 µm). Coarse particles exhibit much lower froth recoveries than fines because they readily drain through the froth when they detach from bubble surfaces, whereas detached fines tend to remain within the froth and still report to the concentrate. Coarse particle recovery tends to therefore be much more sensitive to froth-phase conditions, as demonstrated by Rahman et al. (2012) and Tabosa et al. (2013).

FROTH CARRY RATE, LIP LOADING, AND FLOTATION CIRCUITS

Froth is a three-phase mixture made up of air, solids, and water, with air contributing the largest component by volume. Froth stability is affected by many parameters. Regardless of the relative froth stability, as froth is largely made up of air, there are limits to how much mass froth can physically support and transport before it collapses upon itself.

Before 1995, lip loading was the only way metallurgists could measure a flotation cell's capacity to recover concentrate. The units used were metric tons per hour per meter (t/h/m) of lip length. By adopting column flotation parameters such as froth capacity in grams per square centimeter per minute ($g/cm^2/min$), Outotec came up with a new term for its TankCells using metric tons per square meter per hour ($t/m^2/h$). This is known as the *froth carry rate* (FCR) and is defined by how much material (metric tons) is transported by the froth over a specific area (square meters) in a given time frame (hours). Based on many years of experience together with metallurgical surveying of existing operating flotation operations, a design range of FCRs for different froth flotation duties has been established (Table 1).

Table 1 Typical froth carry rate ranges for banks of cells in base metal sulfide duties

Flotation Duty	Rougher	Scavenger	Cleaner
Froth carry rate, $t/m^2/h$	1.5–0.8	0.8–0.3	2.0–1.0

Source: Bourke 2002

The values given in Table 1 are design rules of thumb that refer to whole banks of flotation cells, and individual cells in the bank may have higher or lower values. Particle size and mineral type will also have an influence on these design values, as dry solid specific gravity will vary between different minerals; for example, galena = 7.5 t/m^3 is much denser than chalcopyrite = 4.2 t/m^3. The values given in Table 1 are representative of typical base metal sulfide operations with a feed particle size P80 of greater than 80 µm. For nonsulfide minerals, much higher FCRs have been reported. For example, in an iron ore reverse flotation application, the FCR varied from 10–40 $t/m^2/h$ depending on which section of the flotation concentrator was surveyed (Miettinen et al. 2013). The FCR limits, both high and low, for a given duty are likely a function of particle concentration, particle size distribution, and particle specific gravity. However, no first-principal method of prediction of these limits exists, though attempts have been made by some researchers (Espinosa-Gomez et al. 1988).

A related concept to FCR and mass transport of the froth is *lip loading*. This is defined as the mass of solids passing over the launder lip per hour per unit length, and is expressed in units of metric tons per meter per hour. When considering if a given flotation cell froth surface area is suitable, it is useful to think first in terms of the overall "froth handling strategy." After the FCR has been confirmed in the correct range, the lip loading should also be calculated and kept at less than 1.5 t/m/h.

FCR and lip loading are important parameters to be aware of to avoid a situation where there is too much or too little solids in the froth phase. Both of these conditions have a negative effect on either the froth stability or mobility and hence performance of a flotation cell (Morar et al. 2014). With insufficient solid particles in the froth phase, the froth stability is significantly reduced and the froth is brittle and breaks down readily. This is often seen toward the end of a rougher bank of cells where very little mass is floating.

Conversely, when there are too many solids in the froth, the froth becomes immobile and the weight of the solids can overcome the carrying capacity of the froth, leading to froth collapse. This sometimes occurs at the beginning of a rougher bank if the flotation kinetics are extremely fast and a lot of mass is trying to float, or also in cleaning duties. Both of these situations result in a significant increase in particle drop-back to the bulk slurry phase, and poor transport of the mineral particles to the launder lip (froth recovery), which reduces the overall froth recovery and hence flotation cell performance.

The FCR must be taken into account when considering a typical base metal or coal flotation circuit. As eluded to earlier, the feed slurry will normally contain both fast- and slow-floating components, and this leads to a curved recovery response plot when performing a laboratory test, as shown in Figure 3.

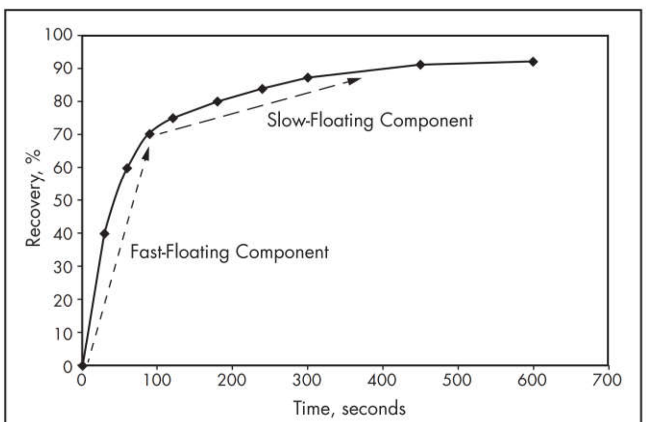


Figure 3 Typical recovery versus time plot for sample with fast- and slow-floating components

In the full-scale circuit, the recovery response shown in Figure 3 means that the majority of the mass will be recovered from the first few cells. So in a typical bank of six cells, the first two cells may be responsible for 70%–80% of the valuable mineral recovered from the entire bank, whereas the last four cells would recover the final 20%–30%. This is a significant difference and shows that a different approach is required in terms of how these cells are designed and operated.

The implications of this recovery distribution can often lead to problems with the FCR in a full-scale plant. If a flotation circuit was designed with all six cells having the same froth area, by simply calculating an average FCR over all cells using the aforementioned example, the first two cells would probably be overloaded (i.e., FCR too high) and the last few cells would be underloaded (i.e., FCR too low). Neither scenario is ideal, and both would lead to less-than-optimum flotation cell performance. The best solution is to tailor each flotation cell design to the expected mass recovery using detailed and robust laboratory or pilot test data. In practice, this usually means adjusting the flotation cell launder type and/or cell crowding configuration down the bank to achieve the best design. It is also beneficial to use an increasing gas rate profile as use of lower gas rates in the cells at the head of a bank reduces the risk of froth overloading and excessive entrainment recoveries. Selectivity and recovery have both been observed to increase in a flotation bank with an increasing gas rate profile to that achieved when the same gas rate was used in all cells (Cooper et al. 2004). Staged addition of collector down the bank of cells can also be used to better manage the distribution of the mass pulled to concentrate.

Having the FCR outside of the ideal range is also an issue at sites where the feed grade has changed significantly since the original process design was conducted. For example, if the feed grade is 50% lower than when the flotation circuit was designed, it can be expected that, all things being equal, the mass recovery would also decrease by a similar amount. The result will be that FCRs are probably lower than the ideal ranges, and froth stability and flotation cell recovery suboptimal. Fortunately, this situation can be rectified quite easily by retrofitting additional crowding to the flotation cells (to reduce the froth surface area and increase the FCR), and this is often conducted by equipment vendors.

Another positive aspect when retrofitting froth crowding or additional froth launders is that this usually results in a reduced average froth transport distance. Froth transport distance is the distance that a particle may have to travel from the froth surface to the closest launder lip, and it is heavily influenced by the selected launder configuration. Therefore, all other things being equal, the average residence time of a particle in the froth will be reduced and the probability of particle detachment and drop-back to the slurry phase is reduced. This can be especially important in improving recovery of leanly liberated coarse particles at the back of a rougher circuit.

WAYS TO MANIPULATE FROTH

FCR and lip loading in a flotation cell are important parameters when considering froth recovery and cell performance. These froth parameters are determined by the amount of mass recovered from a given flotation cell, together with the froth area or lip length available, which is in turn determined by the flotation cell design. For this reason, flotation cell vendors often have several launder types for a given cell size. Consider the cross-sectional froth areas of flotation tank cells with different launder types outlined in Figure 4. The flotation tank cells outlined in the figure all have the same tank diameter and similar central froth crowder size. The launder designs depicted represent some of the most commonly available launder configurations used in flotation cells, and it should be clear that, as drawn from left to right, the froth area decreases significantly because of the launder(s) placement and also the tank shape providing froth crowding.

The different launder configurations shown in Figure 4 do not significantly affect the tank volume and hence flotation residence time. Therefore, the different froth surface area and lip lengths can be used to optimize the flotation cell design for particular duties in a plant based on the expected FCR and lip loadings (e.g., roughing, scavenging, and cleaning). Some vendors have taken this concept a step further by offering multiple launder types within the same cell, as well as concentric designs.

Most of the strategies and comments mentioned so far in this chapter are for flotation cell design in terms of froth management for a greenfield project where new equipment will be designed to suit. However, there are also strategies for manipulating froth in an existing operation. In many ore bodies there is a very fast-floating component in the ore, which may overload the first cell resulting in very high FCRs. Operational parameters such as gas rate, froth depth, and the amount and type of reagent can be manipulated to change the mass recovery profile down a bank with the objective of improving concentrate grades and recoveries. Staged reagent addition can also be employed.

Another way to permanently adjust the amount of fast-floating material reporting to the first flotation cell is to split the new feed to both the first and second cells; that is, send a portion of the new feed straight to the second cell. This is known as split feeding. Split feeding takes advantage of the froth area of both the first and second cell to recover any

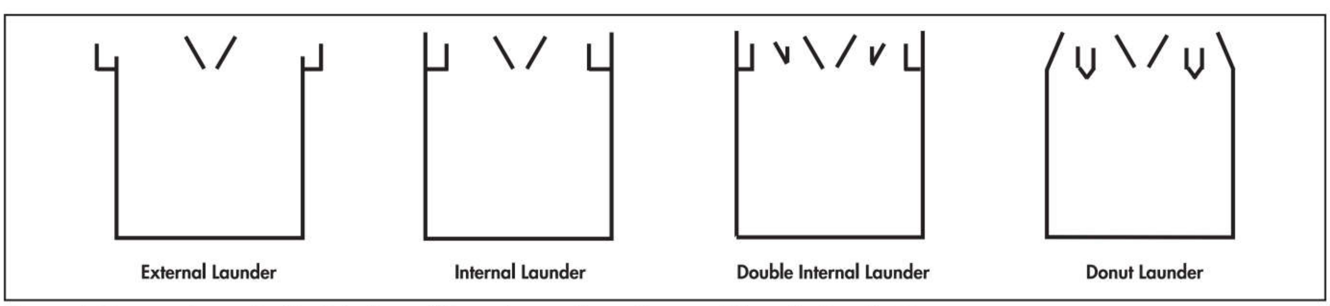


Figure 4 Commonly available flotation cell launder configurations and the effect on froth area

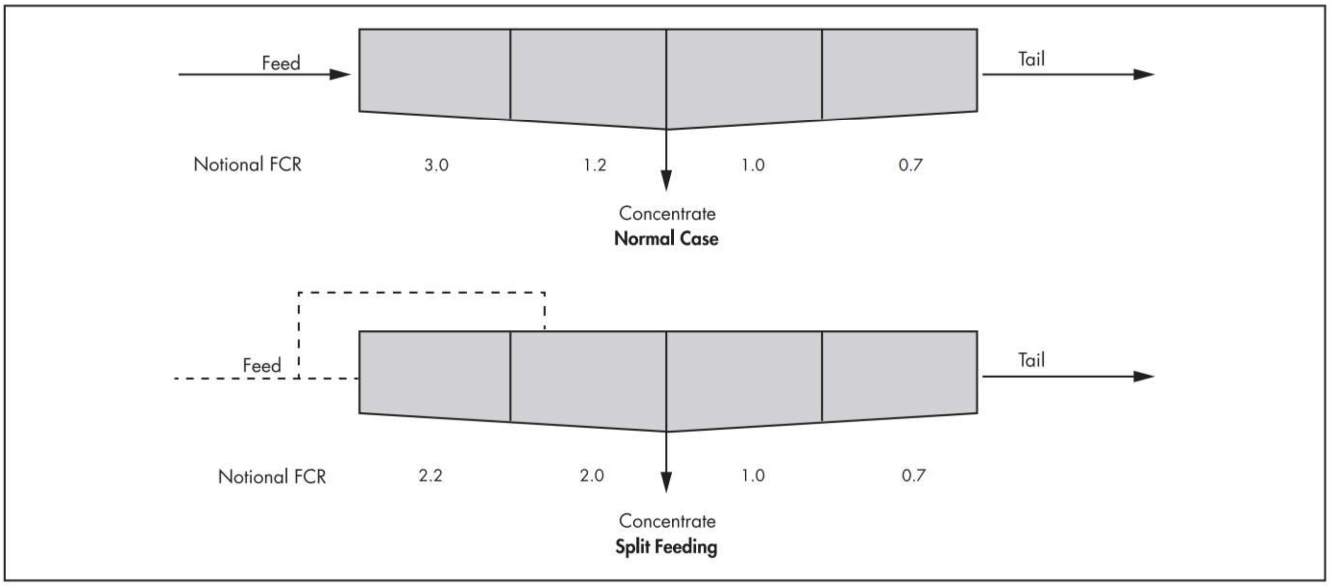


Figure 5 Conceptual diagram of split feeding and the effect on cell froth carry rate

fast-floating component in the ore instead of just the first cell. This thereby tends to average out the FCRs over both cells and produce an overall higher-grade concentrate (Figure 5).

The split feeding concept is particularly relevant for cleaner duties that have very fast kinetics. It is also relatively easy to implement as a trial in an operating flotation circuit using temporary piping and valves. With split feeding, sending a portion of the new feed directly to the second cell will reduce the number of flotation stages and residence time for that component of the feed. If the tailings from the bank of cells are open circuit, then measures should be taken to ensure that a suitable number of flotation stages and residence time remain after the second cell to minimize slurry short-circuiting and a potential loss in recovery.

In a typical base metal flotation concentrator scavenging circuit, it is commonplace to target the recovery of leanly liberated, coarse composite particles. Because of their lean liberation and coarse particle size, these particles are usually weakly attached to a bubble and hence easily detached in the froth phase, and therefore poorly recovered into the launder. One way to increase the recovery of these particles is to transport them as quickly as possible over the launder lip when they reach the froth phase, which can be done by minimizing the froth depth as well as froth transport distance.

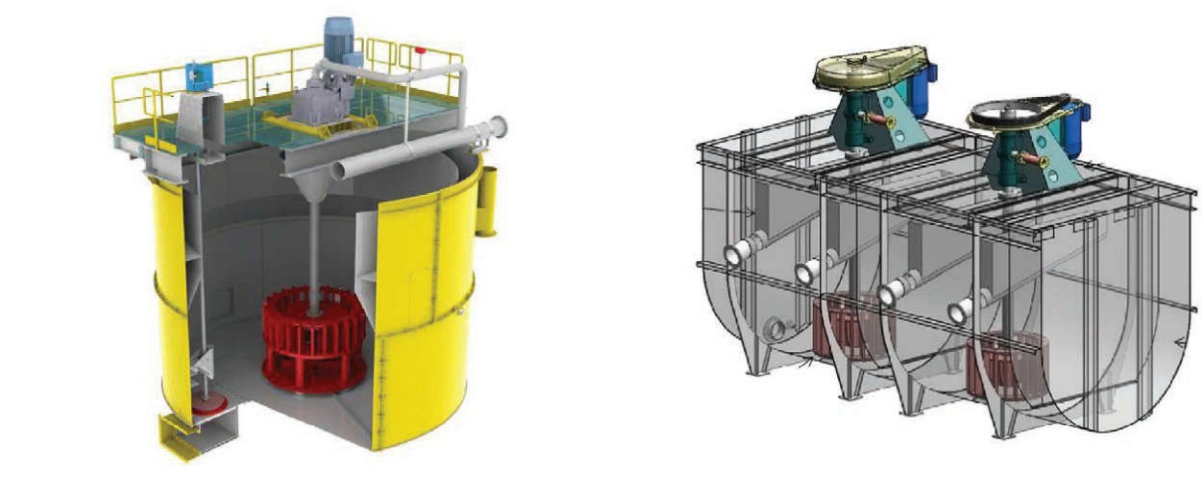
Another method to optimize flotation cell design to suit the expected froth characteristics is to alter the overall tank shape. Two main mechanical flotation cell tank types are currently available: those based on a cylindrical tank (TankCell) and those based on a trough-type tank. An example of each is shown in Figure 6.

There are several differences between the tank types shown in Figure 6 in terms of launders, air control, reagent addition, and so forth. In terms of froth management, the trough-style tank generally has a much higher surface-area-to-volume ratio than a tank cell and hence is particularly suited to duties with high mass recoveries, such as coal flotation. Depending on the comparative cell sizes, the transport distance may also be significantly longer for a trough-type flotation cell. Hence there are several considerations when evaluating which tank shape is the best suited for a particular flotation application.

In terms of direct froth quality monitoring, most recent developments in this area have come from advances in camera technology and algorithms to continuously evaluate the camera output. Many vendors now offer small, easy-to-install video cameras designed to sit above the froth surface and continuously monitor the froth characteristics, which can then be used for process control. Froth properties that can be measured include froth velocity, bubble size, bubble stability (breakage), froth color, froth direction, and so on. To date, the most widely used parameter for process control is simply the froth velocity, which is normally used as a proxy for the actual mass recovery from the flotation cell.

The froth velocity (and froth recovery) can generally be raised by increasing the amount of air being added to the flotation cell. Too much air, however, has a detrimental effect on recovery, as it results in excessive turbulence at the pulp–froth interface, disturbing the froth phase and leading to excessive entrainment of unwanted mineral particles into the collection launder as well as more coarse particle drop-back (Hadler et al. 2010). The optimum air rate needs to be established for a particular flotation cell through experimental testing. The optimum air rate will have been exceeded if boiling is observed at the froth surface, and therefore this condition should be avoided.

Another way to increase froth velocity is to reduce the froth bed depth by increasing the flotation cell slurry height set point. With a shorter froth depth, the froth residence time is reduced and the solids concentration on the froth surface is also reduced, hence the froth has more mobility and tends to move to the launder faster (i.e., faster froth velocity). A shallower froth also means there is less bubble coalescence, and therefore, usually a lower-grade product is removed from the flotation cell but often at a higher overall recovery. To maximize recovery, Crosbie et al. (2009) recommend that the froth depth used should not exceed 70% of the maximum achievable froth height measured in a froth stability column. At this point, froth recovery was observed to decrease significantly



Courtesy of Outotec Pty Ltd.
Figure 6 Two main types of mechanical flotation cells used in the industry

because of significant froth coalescence. This point often cannot be maintained in a scavenger because the recommended froth depth is so low that it would result in pulping and therefore excessive gangue entrainment. Accurate froth depth measurement and control philosophies are therefore important in scavenging applications to enable low froth depths to be employed.

Air addition rate and froth depth are the two main variables to adjust froth velocity in a flotation cell fitted with a froth camera. It is also routine to change the froth properties by adjusting the amount of reagents added to a flotation cell. Generally, increasing the amount of frother or decreasing the amount of collector will increase the froth velocity. When using these variables to control the froth performance down a flotation bank, one also must consider the need to distribute the mass recovered by each cell to optimize froth stability and mobility and reduce gangue entrainment.

These reagents (and others, such as depressants), together with components in the ore itself, can often have synergistic effects. Consequently, the best strategy for reagent addition and control is usually determined on a plant-to-plant basis. To increase froth velocity, the cost of adjusting air addition rate or froth depth typically is significantly less than the cost of adding additional frother; therefore, one should adjust the air and froth depth first before adding additional reagents.

FROTH WASHING AND HANDLING

Two important aspects of froth management are the processes of froth washing and mechanical froth removal. Froth washing in the context of column flotation is discussed in Chapter 7.2, "Column Flotation." The discussions here focus mainly on mechanical flotation cells, such as Outotec high-grade cells, which have a deeper froth depth design and utilize froth washing.

The process of froth washing is carried out by introducing clean water into the froth, with that clean water displacing some or all of the water already in the froth. Froth washing improves metallurgical performance in flotation cells in two ways: first by increasing the flow of water draining between bubbles and washing out entrained gangue; and second by increasing bubble coalescence, which results in a crowding effect on the reduced bubble surface (Kaya and Laplante 1990). Froth washing is particularly useful in washing penalty elements present as hydrophilic minerals back into the slurry phase (e.g., some uranium and fluorine minerals). Several operating plants would incur concentrate smelting penalties if they had not implemented froth washing to remove these elements.

The increased bubble coalescence caused by froth washing also affects the flotation cell froth recovery. Therefore, although froth washing can technically be used anywhere in the flotation circuit, it is usually used in flotation duties where the product grade is of prime importance, such as the recleaning or final cleaning stages. Also, the additional water added to the froth during froth washing does result in the bulk slurry density decreasing, and this reduces the flotation bank residence time. In a greenfield project, this can be allowed for by increasing flotation capacity. However, an existing operation contemplating froth washing should take this extra volume of water into account when considering plant residence time. The overall effect of froth washing is usually a higher-grade product to be recovered to the launder at a lower cell stage recovery.

Typically, froth wash water is added to froth by sprays or streams of water delivered by a froth wash-water delivery system. The water can be introduced from a shallow trough suspended above the froth surface or directly from wash-water piping. An example of each of these systems is shown in Figure 7. Fine sprays are not normally used because of their propensity to become blocked with fine particles and scale from the water. In both of the examples in Figure 7, water is added above the froth surface.

Another way of introducing wash water to the froth is submersed delivery, that is, below the froth surface. This can be done by having the delivery system submersed below the froth surface as is sometimes seen in column cells. Another method of introducing wash water above or below the froth

Figure 7 Suspended (A) wash-water trough and (B) wash-water ring providing wash water

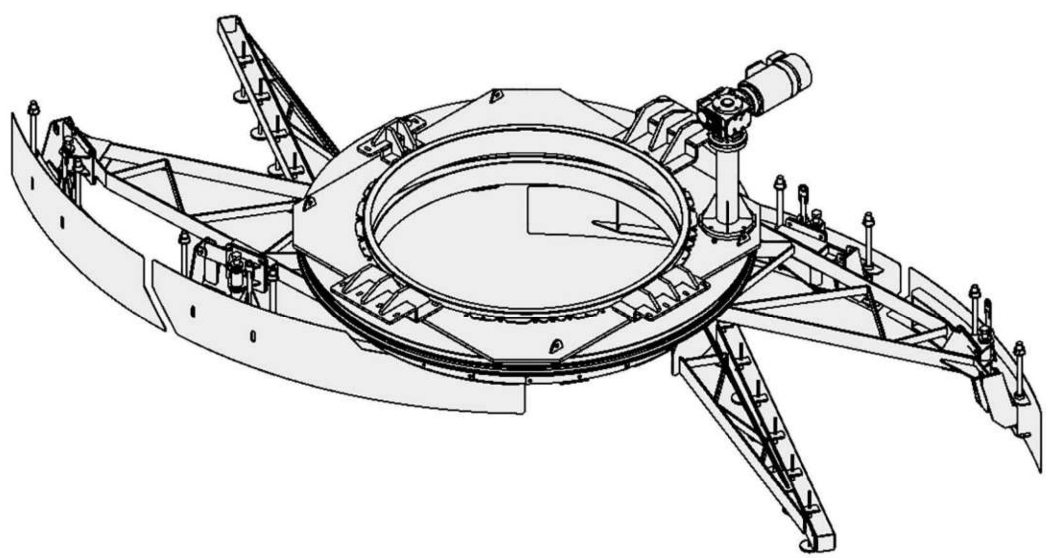
is via a somewhat novel combined froth scraping and washing system developed by Outotec (Figure 8). The combined froth scraping and washing system is typically fitted under the bridge in a tank-style flotation cell, and has an auxiliary drive and slewing ring arrangement to drive the blades continuously around the froth area. The blades sweep out an arc and continuously push the uppermost layers of froth toward and over the launder lip.

Fitted behind the scraper blades are froth wash-water channels. These channels fill with wash water and allow it to run out to the full length of the channel. Adjustable stems with exit holes are fitted, which allow the wash water to run down the stems and fan out. Both the blades and the stems are height adjustable, and the stems can be adjusted to above or below the scraped froth level.

The number of blades and wash channels are adjustable to suit the cell size and froth characteristics. To date, this combined froth scraping and washing system has found use in particularly tenacious froths (e.g., coal flotation, molybdenum cleaning), where mechanical removal of the froth has shown to improve froth recovery and cell performance.

Another mechanical method of froth removal that has been used in flotation machines for many decades is rotating froth paddles. These froth paddles are typically mounted adjacent and parallel to the launder lip (Figure 9). The paddles rotate at a fixed speed to assist with scooping froth over the lip into the collection launder.

The use of froth paddles is limited to trough-shaped flotation cells, as they are mounted adjacent to the launder lip. Froth mobility can often be an issue with trough-style cells because of the lack of internal froth crowding directing the froth flow. These paddles are still used today at processing plants with very sticky froth (e.g., rare earth oxide flotation, spodumene flotation, coal flotation) and are also seen in very coarse flotation duties (e.g., apatite flotation) where they help lift coarse particles of up to several millimeters in size over the launder lip.



Adapted from Outotec Pty Ltd.

Figure 8 Combined froth scraping and washing system

Figure 9 Froth paddles together with trough-style flotation cells (partially empty)

REFERENCES

Achaye, I., Wiese, J., and McFanzean, B. 2015. Effect of particle size on froth stability. Presented at Flotation '15, Cape Town, South Africa, November 16–19.

Ata, S. 2012. Phenomena in the froth phase of flotation: A review. *Int. J. Miner. Process*. 102-103:1–12.

Ata, S., Ahmed, N., and Jameson., G.J. 2003. Gangue drainage in flotation froths. Presented at the XXII International Mineral Processing Congress, Cape Town, South Africa, September 28–October 3.

Barbian, N., Ventura-Medina, E., and Cilliers, J.J. 2005. Mineral attachment and bubble bursting in flotation froths. In *Centenary of Flotation Symposium*. Melbourne, Victoria: Australasian Institute of Mining and Metallurgy. pp. 321–327.

Bourke, P. 2002. Selecting flotation cells: How many and what size? *Output* 1:5.

Cooper, M., Dahlke, R., Scott, D., Gomez, C.O., and Finch, J.A. 2004. Impact of air distribution profile on banks in a Zn cleaning circuit. *CIM Bull.* 97(Oct.): Paper 13.

Crosbie, R., Runge, K., McMaster, J., Rivett, T., and Peaker, P. 2009. The impact of the froth zone on metallurgical performance in a 3m^3 RCS flotation cell. Presented at Flotation '09, Cape Town, South Africa, November 9–12.

Espinosa-Gomez, R., Yianatos, J., Finch, J., and Johnson, N.W. 1988. Carrying capacity limitations in flotation columns. In *Proceedings of the International Symposium on Column Flotation*. Edited by K.V.S. Sastry. Littleton, CO: SME. pp. 143–148.

Farrokhpay, S., and Zanin, M. 2012. Synergic effect of collector and frother on froth stability and flotation recovery: An industrial case. In *Proceedings of the 11th AusIMM Mill Operators Conference*. Melbourne, Victoria: Australasian Institute of Mining and Metallurgy. pp. 145–150.

Gorain, B.K., Franzidis, J.P., and Manlapig, E.V. 2000. Flotation cell design: Application of fundamental principles. In *Encyclopedia of Separation Science*. Vol. II. San Diego: Academic Press. pp. 1502–1512.

Hadler, K., Smith, C.D., and Cilliers, J.J. 2010. Recovery vs mass pull: The link to air recovery. *Miner. Eng.* 23(11-13): 994–1002.

Harris, C.C. 1976. Flotation machines. In *Flotation: A.M. Gaudin Memorial Volume 2.* Edited by M.C. Fuerstenau. New York: AIME. pp. 753–815.

Kaya, M., and Laplante, A.R. 1990. Froth washing and froth vibration in mechanical flotation machines. SME Preprint No. 90-30. Littleton, CO: SME.

Li, C., Runge, K., Shi, F., and Farrokhpay, S. 2016. Effect of flotation froth properties on froth rheology. *Powder Technol.* 294:55–65.

Lovell, V.M. 1976. Froth characteristics in phosphate flotation. In *Flotation: A.M. Gaudin Memorial Volume 2*. Edited by M.C. Fuerstenau. New York: AIME. pp. 597–621.

Miettinen, T., Uliana, A., Araujo de Souza Franco, G., Sergio de Oliveria, P., and Murphy, B. 2013. TankCell flotation at Samarco's Germano concentrators. In *Proceedings of Iron Ore 2013*. Melbourne, Victoria: Australasian Institute of Mining and Metallurgy. pp. 441–444.

Morar, S.H., Bradshaw, D.J., and Harris, M.C. 2014. Assessment of froth stability down a flotation bank. In *Proceedings of the XXVII International Mineral Processing Congress: IMPC 2014*. Edited by J. Yianatos. Santiago, Chile: IMPC. pp. 946–954.

Neethling, S.J., and Cilliers, J.J. 2003. The impact of operating variables on flotation performance: A simulation study. In *Proceedings of the XXII International Mineral Processing Congress*. Marshalltown, South Africa: Southern African Institute of Mining and Metallurgy. pp. 874–881.

Rahman, R.M., Ata, S., and Jameson, G.J. 2012. The effect of flotation variables on the recovery of different particle size fractions in the froth and the pulp. *Int. J. Miner. Process*. 106–109:70–77.

Tabosa, E., Runge, K., and Duffy, K. 2013. Strategies for increasing coarse particle flotation in conventional flotation cells. Presented at Flotation '13, Cape Town, South Africa, November 18–21.

Ventura-Medina, E., Barbian, N., and Cilliers, J.J. 2003. Froth stability and flotation performance. In *Proceedings of the XXII International Mineral Processing Congress*. Marshalltown, South Africa: Southern African Institute of Mining and Metallurgy. pp. 937–945.