Further Reading

Anfruns JF and Kitchener JA (1977) Rate of capture of small particles in flotation. *Transactions of the Institution of Mining and Metallurgy*, *Section C* 86: C9–C15.

Blake TD and Kitchener JA (1972) Stability of aqueous films on hydrophobic methylated silica. *Journal of the Chemical Society*, *Faraday Transactions I* 68: 1435–1442.

Blake TD (1993) Dynamic contact angles and wetting kinetics. In: Berg JC (ed.), ch. 5. *Wettability*. New York: Marcel Dekker.

Collins GL and Jameson GJ (1976) Experiments on the flotation of fine particles: the influence of particle size and charge. *Chemical Engineering Science* 31: 985–991.

Crawford R and Ralston J (1988) The influence of particle size and contact angle in mineral flotation. *International Journal of Minerals Processing* 23: 1–24.

Dai Z, Dukhin SS, Fornasiero D and Ralston J (1998) The inertial hydrodynamic interaction of particles and rising bubbles with mobile surfaces. *Journal of Colloid and Interface Science* 197: 275–292.

Derjaguin BV and Dukhin SS (1960–61) Theory of flotation of small and medium-size particles. *Transactions of the Institute of Mining and Metallurgy* 70: 221–246.

Diggins D, Fokkink LGJ and Ralston J (1990) The wetting of angular quartz particles. *Colloids and Surfaces* 44: 299–313.

Drelich J and Miller JD (1992) The effect of surface heterogeneity on pseudo-line tension and the flotation limit of fine particles. *Colloids and Surfaces* 69: 35–43.

Fielden ML, Hayes RA and Ralston J (1996) Surface and capillary forces affecting air bubble–particle interactions in aqueous electrolyte. *Langmuir* 12: 3721–3727.

Hewitt D, Fornasiero D, Ralston J and Fisher LR (1993) Aqueous film drainage at the quartz–water interface. *Journal of the Chemical Society*, *Faraday Transactions* 89: 817–822.

Hewitt D, Fornasiero D and Ralston J (1995) Bubble particle attachment. *Journal of the Chemical Society*, *Faraday Transactions* 91: 1997–2001.

Israelachvili JH (1991) *Intermolecular and Surface Forces*, 2nd edn. London: Academic Press.

Laskowski JS and Ralston J (1992) *Developments in Mineral Processing. Colloid Chemistry in Mineral Processing*. Amsterdam: Elsevier.

Lynch AJ, Johnson NW, Manlapig EV and Thorne CG (1981) *Mineral and Coal Flotation Circuits*: *Their Simulation and Control*. Amsterdam: Elsevier.

Miklavcic SJ, Horn RG and Bachmann (1995) Colloidal interaction between a rigid solid and a fluid drop. *Journal of Physical Chemistry* 99: 16357–16364.

Ralston J (1992) The influence of particle size and contact angle in flotation. In: *Colloid Chemistry in Mineral Processing*, ch. 6. Amsterdam: Elsevier.

Scheludko A, Toshev BV and Bojadjiev DT (1976) Attachment of particle to a liquid surface (capillary theory of flotation). *Journal of the Chemical Society*, *Faraday Transactions* 72: 2815–2828.

Schulze HJ (1983) *Physico-chemical Elementary Processes in Flotation*: *An Analysis from the Point of View of Colloid Science Including Process Engineering Considerations*. Amsterdam: Elsevier.

Sutherland KL (1948) Kinetics of the flotation process. *Journal of Physical Chemistry* 52: 394–425.

Sutherland KL and Wark IW (1955) *Principles of Flotation*. Melbourne: Australasian Institute of Mining and Metallurgy.

Ye Y and Miller JD (1989) The significance of bubble–particle contact time during collision in the analysis of flotation phenomena. *International Journal of Mineral Processing* 25: 199–219.

Column Cells

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Introduction

History

The first pneumatic flotation cell, which used air sparging through a porous bottom and horizontal slurry flow, was patented in 1914 by Callow. The first countercurrent column flotation device was designed and tested by Town and Flynn in 1919. Cross-current pneumatic flotation machines were widely used in industry in the 1920s and 1930s, but were later replaced by the impeller-type flotation devices in mineral-processing plants. Dissolved-air flotation became the main type of flotation for water treatment applications. These substitutions were the result of the absence of effective and reliable air spargers for fine bubble generation and the lack of automatic control systems on the early columns. During this period, both the poor flotation selectivity and entrainment of slimes characteristic of impeller-type cells were offset by the use of complex flow sheets using large numbers of cleaner stages and recycle lines. Column flotation devices were reintroduced for mineral processing in Canada by Boutin and Wheeler in 1967, at which time washwater was added to the froth to eliminate entrainment of hydrophilic materials to the float product. By the late 1980s column flotation had became a proven industrial technology in the mineral industry. These separators are routinely used on their own or in conjunction with other types of devices within separation circuits. This technology is currently being applied to liquid–liquid separations (oil–water, organic solvent–liquid), solid–liquid, or solid–solid separations in many industries.

Comparative Strengths and Weaknesses

Column cells are flotation devices that also act as three-phase settlers where particles move downwards in a hindered settling environment. Within the vessel there is a distribution of particle residence times dependent on settling velocity that may impact on the flotation of large particles. Impeller devices do not suffer from this effect to the same degree but do require higher energy input to suspend larger particles.

The low turbulence in columns means particles usually have low momentum, which in turn may reduce the probability of collection by passing bubbles. As a result, fine particle recovery may be hindered when compared to the capabilities of impeller-type designs.

The mechanism of particle–bubble collision in columns is different from intensive mixing devices such as impeller cells. Under the low intensity mixing caused only by a rising bubble swarm, particle drift from the liquid streamlines is caused mainly by gravity and inertial forces and also by interception, while in mechanical cells, according to many researchers, bubble–particle collision occurs at their relative movement within a turbulent vortex or at adjacent vortices. Also, as velocities of both bubble and particle during the attachment are slower under the quiescent conditions in a column, the contact time is generally higher. Therefore, probabilities of both collision and adhesion (components of attachment probability) are different to those in mechanical flotation processes.

The lower velocity gradient and less intensive shear forces in the vicinity of rising bubbles under low turbulent conditions in a column lead to reduced detachment probability. The latter is most important for improvement of recovery for coarse, heavy or weakly hydrophobic particles.

A column can support a deep froth bed and may use washwater to maintain a downward flow of water in all parts of the vessel. This essentially eliminates the entrainment of hydrophilic particles in the float product when the vessel is used for solid–solid separation. This property, along with the absence of stray flows of feed material to the float product by turbulence, means that column devices are normally superior to impeller-type machines for the selective separation of fine particles.

In immiscible liquid separation duties, columns do not emulsify the material like impeller devices.

The bubbles used in a column are usually generated within the size range that maximizes interfacial surface flux and collection intensity through the vessel. Dissolved air systems nucleate micrometer-sized bubbles on particles which require very low downward liquid velocities in large volume vessels to separate the bubble and water. Also, dissolved air systems cannot provide air hold-up higher than approximately 4–6%, due to limited gas solubility and lower flooding limits caused by the microbubbles. In mechanical cells, bubbles are usually generated by shear action of the impeller; thus, bubble size is dependent on both air flow rate and impeller rotation speed. As such, bubble size cannot be controlled independently of cell turbulence.

The height-to-diameter ratio of a column is significantly higher than the impeller-type machines. As a result, control and consistency of flow are more critical. The column requires much less floor space to operate.

Control Systems

Control systems are designed to maintain separation in a changing environment by maintaining operating variables at their optimum values for process performance. The configuration used depends on the variability of the vessel feed, the ability of the operating and instrumentation staff, the availability of detectors and other parts, capital costs and the goals of the project. The most basic system only controls the interface level, between the aqueous suspension and froth phases, while complex systems can integrate expert systems or other forms of artificial intelligence into a full-grade/recovery adjustment strategy.

All columns perform best when flows are constant, therefore operation should be as close to steady-state conditions as possible. Good control systems limit damage due to variations by maintaining constant flows in earlier stages, establishing a recycle within the column system, or compensating by changing conditions within the vessel.

Level

The goal of a level control system is to maintain a constant aqueous suspension depth despite changes

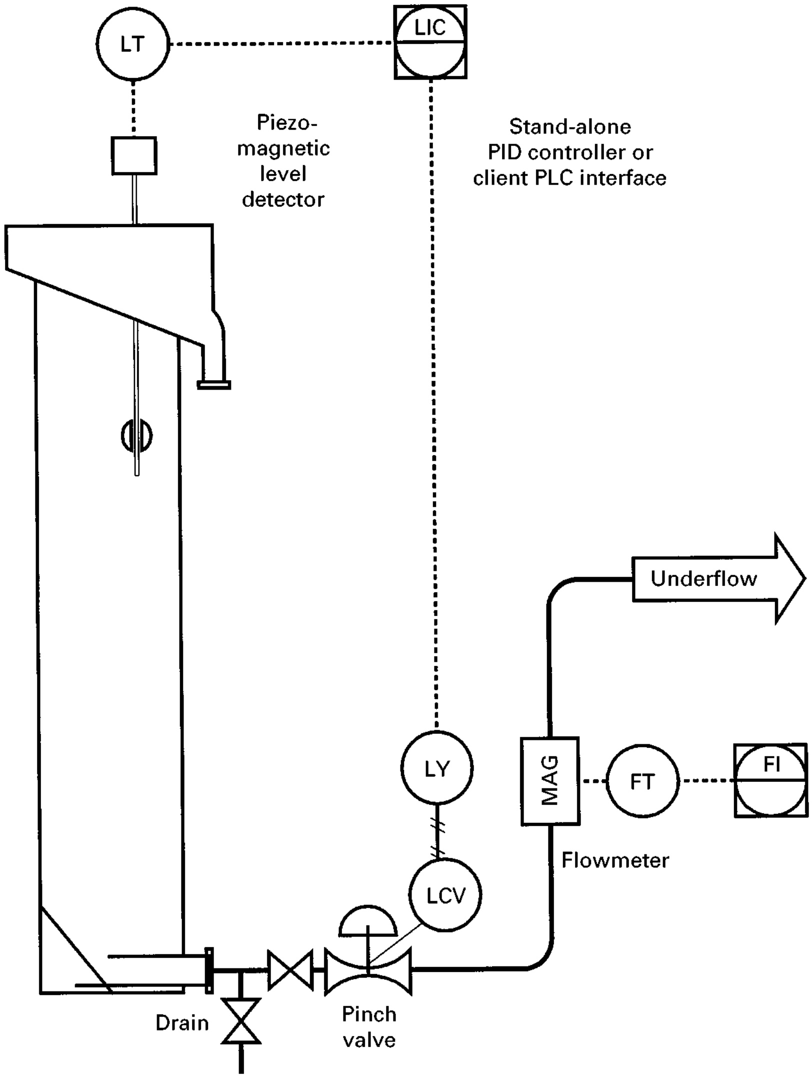

Figure 1 Example of level control loop. LT, level transmitter; LIC, level indicator and control; LY, level D/A signal conversion; LCV, level control device; MAG, magnetic flow detector; FT, flow transmitter; FI, flow indicator; PID, proportional-integral-derivative; PLC, programmable logic controller.

in feed flow, floatable material concentration or air rates. An example of this control is found in **Figure 1**. In water–oil separation, a periodic level rise may be organized to dump an accumulated organic pad. The simplest method of controlling level is to adjust the discharge height of the underflow using a 'gooseneck' or alternative form of gravity control. If this is not possible, then the level must be detected and that signal used to control either a variable-speed pump or control valve through a controller device. Detection devices include floats; pressure, capacitance, conductance, and ultrasonic transducers, or combinations of these devices. The set point for the level is determined from the desired froth depth. Generally, the higher the level, the greater is the recovery of the floating component and the lower its content in the overflow (froth product). In more complicated systems, the level control may be used with froth or oil pad depth data to control overflow grade, with flow-monitoring devices for predictive control based on incoming feed, or multiple monitors to compensate for variations in air rate or feed composition.

Air

The purpose of the air loop is to control a volumetric flow of air through the column or to maintain a three-phase density within the vessel. In basic control systems air rate is controlled manually based on a monitored air flow rate. In slightly more advanced systems, the flow is controlled through an automatic valve to compensate for pressure changes (**Figure 2**).

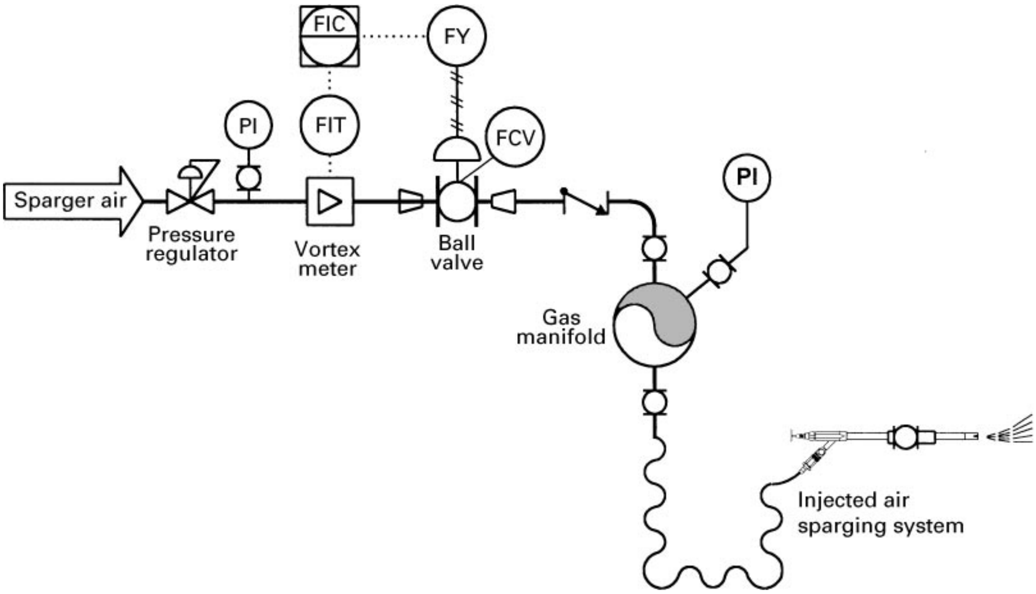

Figure 2 Example of air control loop. PI, pressure indicator; FIT, flow indicator and transmitter; FIC, flow indicator and controller; FY, flow D/A signal conversion; FCV, flow control device.

Air rate may be linked to predictive- or recovery-based systems.

Bias

Bias is defined as a downward flow of liquid through the froth zone. Positive or downward bias is usually used when two suspended substances must be separated from each other. If multiple separation stages are in operation, it is usually used on the last stage. The downward flow of water through the froth is controlled by varying the water rate added to the froth zone. This flow may be monitored by temperature, conductance or by flow differences (water added to froth minus overflow water, or amount of liquid in underflow minus its amount in feed). The actual bias needed depends on the distribution of the water through the froth and the hydrophilic particle sizes.

Bias may be estimated using the difference in slurry flows (**Figure 3**) or, more accurately, by first calculating the liquid volumetric flows using flow and density meters.

Advanced Controls

It is possible – although not common – to control a column to separate according to a grade–recovery response curve. As grade increases or decreases in the feed, level, air rate and bias may be adjusted to achieve the most economical performance. This type of control requires a good predictive model based on theoretical knowledge, past experience and test work that uses information from upstream processes to adjust column parameters in anticipation of changes (feed-forward control). Predictive systems provide feed-forward control and can incorporate either knowledge base or models (statistical or deterministic) into the control loop. Excessive complexity of models or control strategy does not improve the results as the uncertainty in parameters grows. Such a system also requires extensive online detection equipment such as density, flow and pressure meters. When these controls are implemented they are either model-based systems or some form of artificial intelligence (knowledge base, neural network systems based on fuzzy logic principles).

Operating Parameters

Process-operating variables are those inputs to the separator that may change with time and can be used to control the production quantity and quality. These include column control variables such as gas rate, washwater rate and froth or oil pad levels. There are also variables that may be controlled but are usually not even monitored, like bubble size distribution, and variables that depend on other parts of the operation such as volumetric feed rate, and feed solids characteristics: concentration, liberation and particle size distribution.

Gas (Air)

Gas (air) rate is an effective parameter to control separation since the probability of particle collision

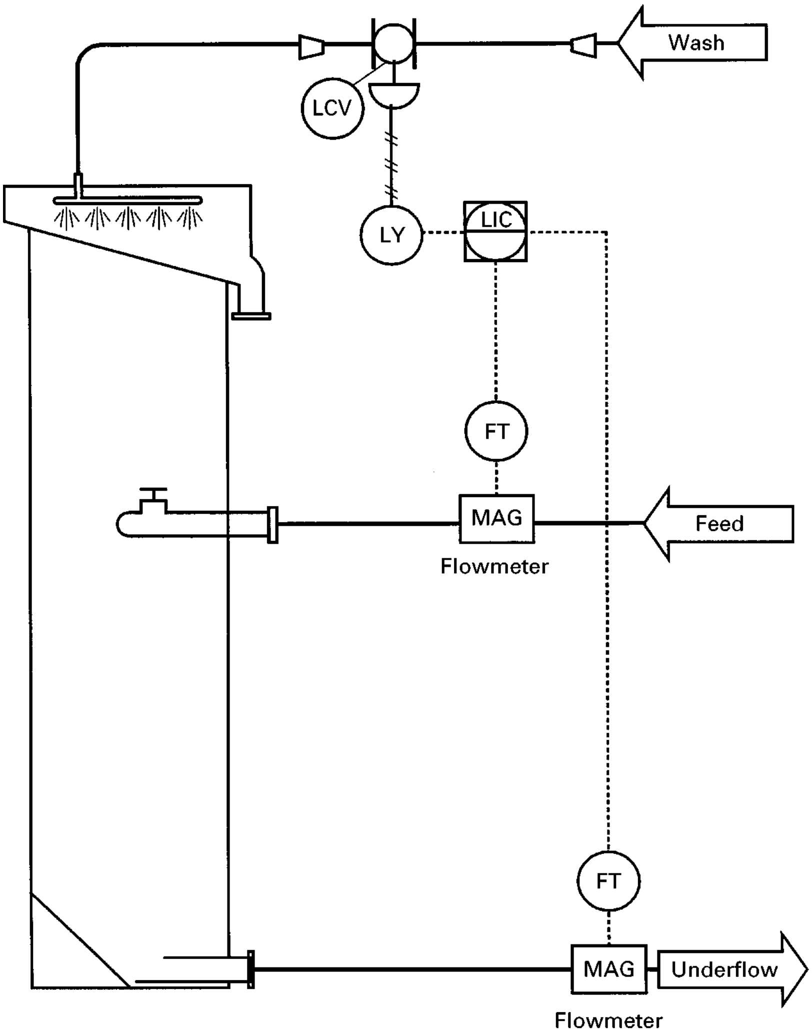

Figure 3 Example of differential feed–underflow bias control loop. LCV, level control device; LY, level D/A signal conversion; LIC, level indicator and control; FT, flow transmitter; MAG, magnetic flow detector.

with bubbles is dependent on the number of bubbles and their size distribution. The maximum particle surface flux removed depends on bubble surface area flux. As surface area flux increases, so does the probability of material–bubble aggregation (collection) within a specific range. This range is bounded by the increased mixing intensity as flooding limits are approached and the increase in bubble size that is usually associated with an increase in gas flow. The total removal capacity, known as carrying capacity, can also be controlled by the gas rate since it is proportional to the specific bubble surface area. The carrying capacity is determined as the maximum amount of material which can be transported into froth in unit time from a unit cross-sectional area of a column. It varies depending on particle size (for solid separation) and density of the floating substance. The carrying capacity can be estimated from the balance of the available bubble surface area and particle surface flux. The normal range of superficial air velocity is 1.0–2.5 cm s^{-1}. In buoyant material separations, high gas rates may reduce the three-phase density of the aqueous suspension within the column to a density lower than that of the product. This will cause an unstable pad that will sink if not quickly removed from the system.

Volumetric Feed Rate

The volumetric feed rate determines the vessel retention time and strongly influences vessel mixing. An increase in superficial suspension velocity results in lower gas limits as flooding will occur at lower gas rates and increases the size of microbubbles which become entrained by downward flow to the underflow. However, higher slurry velocities also decrease the negative influence of mixing on grade and recovery (higher Peclet number) and lessen the retention time difference between fine and coarse particles due to the settling. Typically, superficial feed velocity is 0.5–1.3 cm s^{-1}.

Feed Solids

An increase in the percentage of solids contained in the feed increases the residence time of those solids in the case of constant-column throughput of solids. The maximum solids load is determined by the viscosity of the system and may be only 0.25–2% (weight/weight) for paper de-inking applications to almost 70% for calcite/silica separation.

Washwater

Mineral separation columns can provide a positive bias which causes displacement of the feed liquid phase with washwater in the overflow. This substitution virtually eliminates entrained fines from the overflow product. Washwater distribution on to or into froth and its flow rate should be individually tuned for each application depending on feed and concentrate size distributions, froth stability, height and mobility, and on process objectives. Excessive washwater supply causes froth disruptions, loss of recovery and dilution of products. Typically, superficial washwater flow rate does not exceed 0.15 cm s^{-1}, although optimal rates depend on washwater distribution design and froth rheology. Washwater is not normally used in mineral roughing or scavenging operations, oil–water separations, or systems where entrainment is not a factor.

Froth Depth (Solid Separation)

The froth level maintained within the column is highly variable depending on the application. Some vessels may be operated with no froth, such as oil–water separators, or mineral columns operating on very large particles. In other cases, like molybdenite flotation, a froth as deep as 1.5 m may be run to ensure minimal entrainment and high selectivity. In general, a deep froth gives more opportunities for grade/recovery control and compensates for poor washwater distribution. Froth depth in mineral (solid–solid separation) column flotation typically varies from 15 to 300 cm. The gas hold-up in froth gradually increases upwards due to froth sineresis and drainage along plateau canals. The entrained fine particles return back to the lower (collection) section of the column by net downward liquid flow in the froth (in the case of positive bias). Experimental data confirm that, in some cases, upgrading of the product occurs mainly in the froth zone, and not at the collection stage.

It is important to note that an increase in froth depth decreases the volume of the remainder of the column which may be detrimental to overall performance.

Organic Pad (Liquid Separation)

In an oil separation vessel a hydrocarbon pad may be maintained at the top of the column. A deep pad minimizes water entrainment into the overflow but may increase the stripping of light hydrocarbons. When high air rates are used and the organics pad is not removed, droplets of organic phase may form and drop through the aerated zone of the column. Air rates must be lowered or the organics pad continuously removed as a froth to prevent sinking of the floated organics.

Bubble Size

Some types of spargers allow the change of bubble size distribution at nearly constant overall air rate. Both break-up and coalescence of bubbles occur after formation by the sparging devices which results in an equilibrium size distribution above a certain distance from the spargers. The average and deviation of this distribution depend on the surface tension at the air–water interface and turbulence in the cell. Generally, smaller bubbles provide higher collection intensity and carrying capacity, but loaded microbubbles may sink or be entrained in the downward slurry. Also, maximum gas rate (at column flooding point or transition to a churn-turbulent regime) is reduced with decreasing bubble size, meaning that there is a specific bubble size that gives the maximum upward rising surface area flux. The point of column flooding can be estimated (in the assumption of cross-section flow uniformity and narrow bubble size distribution) from the drift flux model. In many cases a combination of smaller bubbles that provide the separation and coarser transport bubbles that coalesce with the smaller bubbles results in optimal flotation rates.

Column Circuits

Column cells can be used to perform many functions. These include separation within a grinding circuit (unit cell), as an initial (primary or rougher) or scavenging separator whose purpose is maximum recovery of material, or as a final separator (cleaner or recleaner) used to produce a pure product. They can also be used to process bleed streams from other processes. There are many examples of column usage, including base metal and industrial mineral separation, iron ore purification, coal cleaning, solvent extraction and oil–water separation, paint recovery and newspaper de-inking. In addition, columns can be used to remove hydrophobic substances, or materials dissolvable in hydrophobic liquids, from water or soils. Examples are DDT, polycyclic aromatic hydrocarbons (PAHs) or other dangerous chemicals, oil production from tar sands, or the purification or removal of algae or bacteria from cultures. All of these separations fall into three categories: solid–solid, solid–liquid and liquid–liquid separations.

Solid–Solid Separations

In order to get a good separation, the solids present must be liberated: that is, not physically or chemically attached, be suspended in a liquid medium and the flotation kinetics of the materials must be different. One or more stages of separation may be needed, depending on the kinetics and chemistry of the separation. To achieve sharper separation when difference in flotation rate of components is not high and/or material is not completely liberated, complicated flowsheets including multiple recycle lines and regrinding are used. Regrinding operations for middlings are used to avoid over-grinding of the bulk of material as it would cause reduction in flotation rate and selectivity for fine particles. For finely disseminated ores, entrainment is a substantial factor reducing sharpness of separation. Entrainment is a process of particle transfer to froth without their attachment on to bubble surfaces. This phenomenon can be explained by movement of small particles in the wake behind the rising bubble or within the static layer of liquid surrounding it. In machines with intensive mixing (impeller cells) the entrainment can also be caused by local upward slurry flows. These flows are not present in columns therefore reducing overall entrainment intensity and improving separation efficiency. A classical flotation flowsheet includes several cleaning stages generally linked by recycle of the cleaner tailings to previous stages. When more than one material is floatable and separation depends only on degrees of hydrophobicity (molybdenite-chalcopyrite), four to six stages may be required. If insufficient recovery is achieved in the primary vessel (rougher flotation), scavenger cells may be used. In general, all stages do have a common separation goal. For example, silica (impurity) is floated away from hematite in a four stage iron ore circuit in **Figure 4**. This circuit, or variations of it, is common when the valuable product is hydrophilic or an underflow product of the column. The example gives four stages of separation; however, in many cases fewer stages are required.

The circuit for a hydrophobic product is shown in **Figure 5**. The second cleaner stage of this circuit is generally not needed unless the separation is between

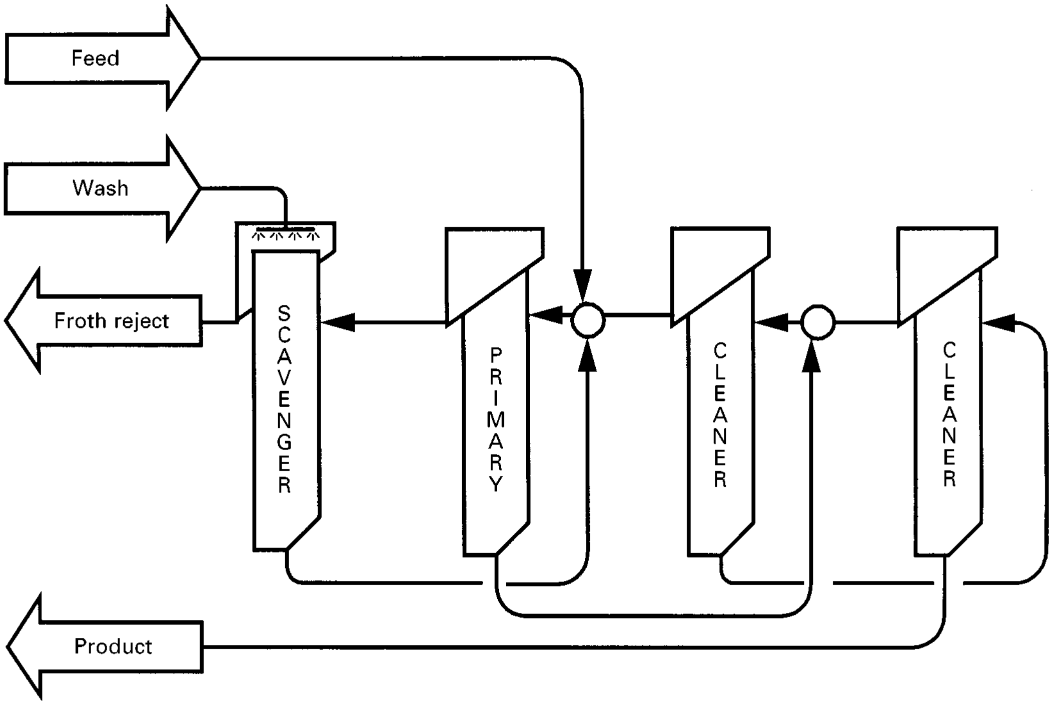

Figure 4 Hydrophilic product, solid–solid four-stage separation circuit. Example of iron ore.

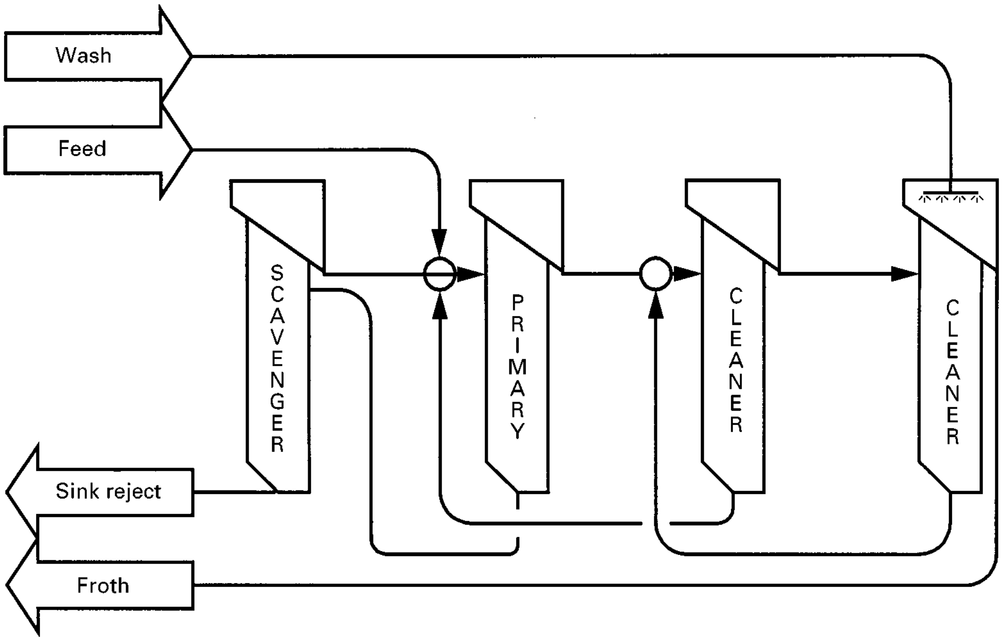

Figure 5 Hydrophobic product, solid–solid four-stage separation circuit. Example of copper or plastics float.

hydrophobic materials with similar flotation rates. As an example, this configuration or variations of it can be used in phosphate, copper, zinc and plastics separations, or for soil remediation.

Solid–Liquid Separations

In many circumstances a solid is present in a liquid stream that must be removed. Flotation is often a viable precursor stage, used to increase the percentage of solids, prior to filtration. This type of system can be used to float coal and associated PAHs from run-off water and upgrade the presentage of solids from p.p.m. levels up to 10–25%. **Figure 6** gives an example of such a circuit where PAHs from coking coal are floated from a contaminated site run-off water without removing the naturally occurring sand and silt.

Flotation can also be considered as an alternative to settling of naturally hydrophobic materials in wastewater treatment. This type of separation may also be used to remove bacteria or algae from water, or many solid substances from reaction vessels.

Liquid–Liquid Separations

Immiscible liquids of any kind can be separated from water by flotation. The bubbles act to increase the kinetics of the naturally floating droplets such as diesel, crude oil, kerosene or the organics used in solvent–liquid extraction processes. Some examples are hydrocarbon separation from water on oil

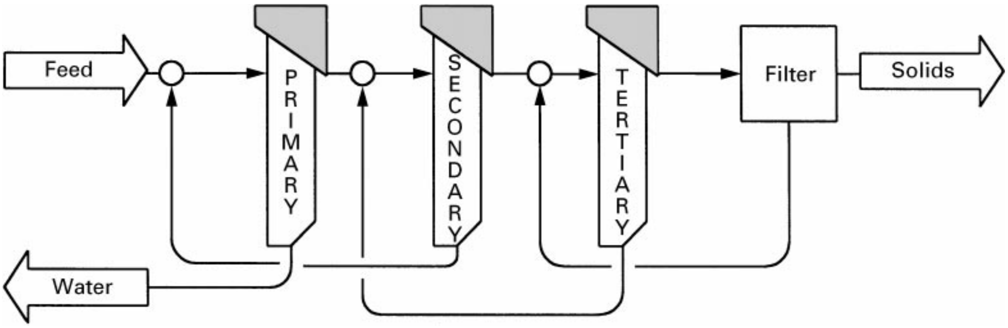

Figure 6 Example of solid–solid separation: PAH from run-off water. Input of approximately 500 p.p.m. solids; filter feed of approximately 24% solids.

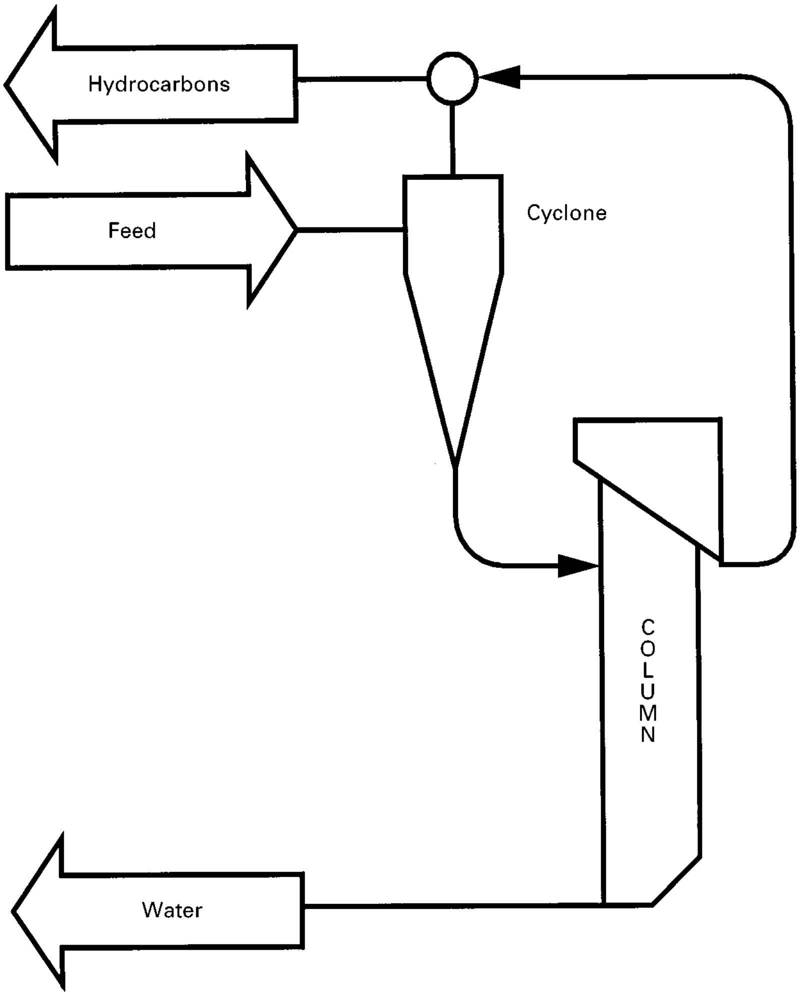

Figure 7 Treatment of oil platform process water; generalized circuit.

production platforms prior to final release of water, site run-off remediation and organics separation in hydrometallurgy. Columns are capable of removing freely floating hydrocarbons but usually not emulsified or dissolved hydrocarbons. In order to remove emulsified forms of hydrocarbons, a pre-aeration unit must be installed.

Oil production application Large amounts of water are involved in the extraction and production of oil. Column cells are used in the water treatment stage of production prior to release of the water back into the environment. In a typical circuit, as shown in **Figure 7**, water from the process is first passed through a cyclone or corrugated plate separator then to a column. The hydrocarbon concentrate from both of these vessels is returned for processing.

Site run-off remediation Sites that contain hydrocarbon contamination such as refineries and distribution depots often have run-off waters that contain entrained hydrocarbons. These can be treated effectively with flotation technology using a circuit containing a column either working on its own or in conjunction with a settling tank. If emulsified hydrocarbons are present, a pre-aeration unit may be required on the column in order to achieve contamination level under 15 p.p.m.

Organic–aqueous separation in solvent–liquid extraction circuits The solvent liquid extraction circuits employed in most hydrometallurgical processes require the removal of essentially all of an organic solvent from an aqueous medium in more than one stream. Initial separation is usually done in settlers. Columns with or without a pre-aeration unit can be used as secondary separation devices prior to filtering. The advantage of columns over many other devices is their ability to compensate for wide fluctuations in both aqueous and organic flows.

Conclusion

Column flotation has become the standard proven industrial flotation technique rather than an experimental method during the last decade. Nevertheless, its use in mineral-processing plants is mainly restricted at present to cleaning operations. The future of flotation equipment development lies in the combination of the advantages of impeller and column flotation and in the use of pneumatic machines in roughers.

As a greater share of flotation operations are used for unconventional areas such as environmental applications (water treatment, soil remediation, etc.) and ultrafine and colloid particle separation, special machines will be developed combining flotation attachment at intensive aeration and mixing conditions and three-phase separation in a quiescent environment. This leads to the concept of pre-aeration in a reactor (a unit for attachment of recovering phase on to gas bubbles) and de-aeration in a separator (a unit for separation of loaded bubbles from the bulk of three-phase suspension). Additional coarser bubbles can be added in a separator as a carrier to enhance the removal of loaded microbubbles by coalescence.

This concept and other types of new combined flotation machines will provide for more effective and efficient separation for a wide range of applications.

See also: **I/Flotation. II/Flotation:** Froth Processes and the Design of Column Flotation Cells.

Further Reading

Agar GE, Huls BJ and Hyma DB (eds) (1991) *Column '91. Proceedings of an International Conference on Column Flotation*, June 2–6, 1991. Sudbury, Ontario, Canada: Canadian Institute of Mining and Metallurgy and Petroleum.

Boutin P and Wheeler DA (1967) Column flotation development. *Canadian Mining Journal* 88: 94.

Finch JA and Dobby GS (1990) *Column Flotation*. New York: Pergamon.

Gomez CO and Finch JA (eds) (1996) *Column '96. Proceedings of the International Symposium on Column Flotation*, August 26–28, 1996. Montreal, Quebec, Canada: Canadian Institute of Mining and Metallurgy and Petroleum.

Pal R and Masliyah J (1991) Process dynamics and control of a pilot flotation column. *Canadian Metallurgical Quarterly* 30: 87–94.

Rubinstein JB (1995) *Column Flotation, Processes, Designs and Practices*. Basel, Switzerland: Gordon and Breach.

Yingling JC (1993) Parameter and configuration optimization of flotation circuits, part I: a review of prior work. *International Journal of Mineral Processing* 38: 21–40.

Column Flotation Cells

See **II / FLOTATION / Froth Processes and the Design of Column Flotation Cells**

Cyclones for Oil / Water Separations

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Synopsis

Though the solid–liquid hydrocyclone has been established for most of the 20th century, satisfactory liquid–liquid separation performance did not arrive until the 1980s. The offshore oil industry had a need for compact, robust and reliable equipment for removing finely divided contaminant oil from water. This need was satisfied by a significantly different type of hydrocyclone, which of course had no moving parts.

After explaining this need more fully and comparing it with solid–liquid cyclonic separation in mineral processing, the advantages that the hydrocyclone conferred over types of equipment installed earlier to meet the duty are given.

Separation performance assessment criteria are listed prior to discussing performance in terms of feed constitution, operator control and the energy required, i.e. the product of pressure drop and flowrate.

The environment for petroleum production sets some constraints for materials and this includes the problem of particulate erosion. Typical materials