inhibits separation. A 2° tilt results in one end of a 12 m long flotation machine being approximately 350 mm higher than the other end of the vessel. This results in one end of the machine flooding while the other end will not remove floated oil. To overcome this problem, one manufacturer has designed a flotation column ISF machine that reduces the impact of pitch and roll to 10 mm at 2° tilt.

The method of bubble generation (eduction) is the same as that used for the four-cell ISF. Sparging was investigated as an alternative, however the bubbles were larger and moved in a linear fashion to the surface. Educed air forms smaller bubbles and exhibits random movement. Both these latter characteristics are desirable as they increase the chance of an air bubble–oil droplet collision.

Since the single-cell ISF has one rather than four cells, theory would predict that its contaminant removal efficiency would be reduced from approximately 90–98% for a four-cell unit to 80–90% for a single cell unit, primarily because the residence time in the single cell unit is some 65% of that in the traditional four cell design. In trials, however, the unit has operated successfully with inlet oil concentrations of between 50 and 1300 ppm, and suspended solids concentrations of 10–50 ppm, and has achieved oil removal efficiencies comparable to the four-cell model, taking into account the reduced residence time in the single cell. In service, actual efficiencies will depend on optimization of flow regime and chemicals (see **Figure 6**).

See Colour Plate 45.

See also: **II/Flotation:** Column Cells; Cyclones for Oil/Water Separations; Historical Development.

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Pre-aeration of Feed

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Introduction

Aeration of slurry is a key element in a flotation system. The extent of aeration influences the performance of flotation machines and the overall recovery process. Flotation can, in general, be divided macroscopically into two subprocesses: selective collection of hydrophobic particles by air bubbles, and separation of bubble/particle aggregates from the pulp containing hydrophilic particles. The method and location of aeration or bubble generation control the mechanism of particle collection by either collision with and subsequent attachment to bubbles, or *in situ* bubble formation on hydrophobic particle surfaces. A flotation machine should be designed to provide an optimal aeration condition for efficient particle collection and a suitable hydrodynamic environment for effective transfer of bubble/particle aggregates from the remaining pulp. Unfortunately, conflicting hydrodynamic environments are usually required for these two sub-processes. It is often difficult – if not impossible – to evaluate theoretically the relative contributions of individual collection mechanisms in a particular flotation device. The limited understanding of the aeration mechanisms in flotation processes is partly responsible for the development of more than 200 flotation cell designs over the years. Many of these designs are not subtle variations in basic hardware, but variations in design principles. Therefore, knowing where and how collection occurs and which aeration method is suitable for a particular application is an important step in a more scientific approach to flotation cell design.

Aeration methods used in flotation can be conveniently categorized as air dispersion and air dissolution. In the air dispersion approach, a stream of air is dispersed into slurry to achieve suitable sizes and population of bubbles. This is accomplished by shearing the air stream into bubbles under mechanical agitation as in mechanical flotation machines, or using in-line static mixers as in Microcels and packing materials as in packed columns. Air can also be dispersed through porous spargers, as used in pneumatic flotation machines or conventional Canadian flotation columns.

With the air dissolution method, on the other hand, the air is dissolved under a pressure of 3–5 atm into slurry for subsequent gas nucleation (or gas precipitation) and cavitation. Bubble formation is then achieved by either releasing gas-supersaturated slurry to atmospheric pressure as in dissolved air flotation, or decreasing the pressure of slurry by aspiration as in vacuum flotation.

Dispersed air flotation is widely used in minerals processing with relatively coarse particles (larger than 20 μm) and high slurry densities (greater than 30% solids). Other areas of applications include solid cleaning, de-inking from recycled paper and bitumen recovery from oil sands. Dissolved air flotation is suitable for municipal water and industrial effluent treatment, due to its capability of generating relatively fine bubbles of less than 100 μm required for recovering particles finer than 10 μm at a slurry density of less than 0.5% solids.

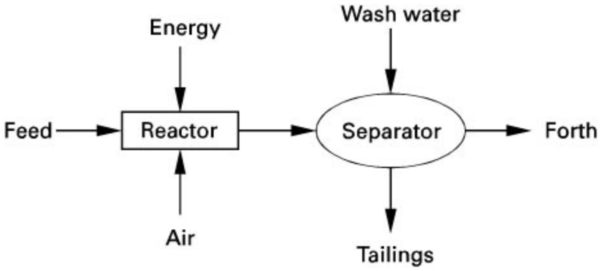

Figure 1 Schematic illustration of the concept of a flotation system consisting of a reactor and a separator.

An emerging trend is to integrate the useful features of dissolved air flotation into dispersed air flotation. The combination of the two bubble-generating mechanisms has led to a new flotation cell design. Traditionally, slurry aeration and flotation separation are performed in the same vessel. Feed aeration followed by flotation separation in a separation vessel (a reactor–separator design), has been evolved with demonstrated higher flotation kinetics. The concept of a flotation system consisting of a reactor and a separator is illustrated in **Figure 1**. The reactor is a vigorous bubble/particle contacting device where particle collection takes place with bubbles formed by both air dispersion and nucleation/cavitation mechanisms. The separator is a quiescent bubble/pulp separation device where the hydrodynamics favour the separation of bubble/particle aggregates from the pulp with essentially no or little turbulence.

With continuing improved understanding of particle/bubble collection mechanisms and the role of aeration in flotation, it is anticipated that pre-aeration of feed will become an important component in modern flotation circuits as a means of increasing flotation kinetics and improving selectivity of fine particles. This article focuses on the fundamentals and recent developments in pre-aeration of feed used in mineral flotation.

Fundamental Basis of Feed Aeration

A theoretical analysis of aeration in a flotation system is complicated. As a result, the development of aeration techniques in flotation is largely based on phenomenological correlations. The feed aeration and subsequent particle collection during the aeration are the combination of features of dispersed and dissolved air flotation. Particle collection by air bubbles in flotation is a multi-step process, involving three phases with interactions among solid/liquid, solid/gas and liquid/gas in the presence of various inorganic and organic species under economical and mechanical constraints. At least two particle collection mechanisms have been considered in flotation.

Direct Contact of a Particle with a Bubble

In this collection process, a particle encounters a bubble, either by relative motion or the turbulence in a flotation system. The probability of the particle being captured by the bubble (P) can be expressed as:

$$P = P_c P_a P_d \qquad [1]$$

where P_c, P_a and P_d are the probability of bubble/particle collision, attachment and detachment, respectively. For a hydrophobic particle, bubble/particle collision determines the particle collection rate governed by hydrodynamic conditions. Hydrodynamic analysis showed that the collision probability between a descending particle with an ascending bubble is given by:

$$P_c = a(d_p/d_b)^n \qquad [2]$$

where parameters a and n are a strong function of hydrodynamic characteristics of the system. Eqn [2] shows that the probability of particle–bubble collision is proportional to the nth ($n \geq 1$) power of the solid particle size (d_p) and inversely proportional to the same power of the bubble size (d_b). For fine particles, small bubbles have to be used to obtain sufficient particle–bubble collisions. The direct contact was analysed between a descending fine particle of $d_p = 10$ μm and a rising swarm of bubbles in a flotation column. A collection zone as tall as 10 m was determined to be essential to ensure at least one collision of the particle with a bubble. This implies an inefficient collection process under conventional column flotation conditions.

To increase the particle–bubble contact frequency, a relatively high turbulence or energy dissipation rate is required, as in mechanical flotation machines. The number of particle–bubble collisions per unit volume and time in a highly turbulent flowing fluid (Z_{pb}) can be expressed as:

$$Z_{pb} = 5N_p N_b[(d_p + d_b)/2]^2(V_p^2 + V_b^2)^{0.5} \qquad [3]$$

where N_p and N_b are the number concentrations of particles and bubbles in the pulp. V_p and V_b are the mean relative velocities of the particles and bubbles (with reference to fluid), which are given collectively by:

$$V_i = 0.33\varepsilon^{4/9} d_i^{7/9}(\Delta\rho/\rho)^{2/3}/\nu^{1/3} \qquad [4]$$

In eqn [4], subscript i refers to bubble or particle, ε is the specific energy dissipation rate, $\Delta\rho$ is the difference in densities of particle i and liquid medium, ρ is the medium density, and ν is the kinematic viscosity. This equation shows that a high energy dissipation rate favours particle–bubble collision. However, vigorous agitation as in mechanical flotation machines may break particle-bubble aggregates, thereby increasing the probability of particle detachment from bubbles and hence decreasing the overall collection rate. In addition, the back mixing (or liquid circulation) caused by increased turbulence may hinder the transport of bubble–particle aggregates out of the turbulent zone, contributing to low flotation kinetics. The incentive to separate the two functions of a flotation machine, i.e. aeration and separation, is evident, as reflected in the reactor–separator design.

In Situ Bubble Nucleation on Hydrophobic Particles

With this mechanism, gas nucleates and bubbles form selectively on hydrophobic particles. The theoretical basis of flotation by gas precipitation or nucleation was proposed in the 1960s and has recently been extended to hydrodynamic cavitation. The gas nucleation mechanism has been used to account for particle–bubble collection in dissolved air flotation. An advantage of this mechanism over a conventional particle–bubble contact mechanism is the elimination of a collision stage, a rate-limiting step in fine particle flotation. However, direct adoption of this technique to mineral flotation faces a number of challenges. Clearly, tiny bubbles in the micro and submicron range generated solely by a gas nucleation mechanism are not sufficient to float coarse mineral particles effectively. However, the collision probability of larger bubbles with the particle–tiny bubble aggregates in the quiescent region may increase. The limited number of bubbles that can be generated by gas nucleation from a supersaturated system does not provide sufficient carrying capacity to float large amounts of solids. To improve solid recovery rates, large volume slurry saturation tanks are needed, presenting extra capital and operating costs.

Alternatively, tiny bubbles and cavities can be formed by the reduction of pressure in a fast-flowing fluid, as indicated by Bernoulli's equation:

$$P_1 + (1/2)\rho U_1^2 = P_2 + (1/2)\rho U_2^2 = \mathrm{C}\,(\text{constant}) \qquad [5]$$

in which U is the water flow velocity at a point where the pressure is P, and ρ is the density of liquid. If the liquid flow velocity exceeds a critical value, the pressure in the liquid stream reduces to a value where the liquid pressure falls below its vapour pressure, at which point cavities form which expand to relieve the differential pressure, a phenomenon called hydrodynamic cavitation. The presence of solids enhances hydrodynamic cavitation due to the increased turbulence and pressure fluctuations around particles in the stream. As in gas-supersaturated systems, cavities would form preferentially on hydrophobic particles relative to energetically unfavourable hydrophilic solid–liquid interfaces. The principal advantage of exploring hydrodynamic cavitation in flotation is that gas supersaturation of slurry is not required and additional air can be introduced into the system for air dispersion. As a result, hydrodynamic cavitation can be readily implemented in mineral flotation systems.

A convenient way of aiding bubble nucleation and cavitation is by aeration in the feed slurry line. The existence of gas nuclei in water has been demonstrated in coagulation, sedimentation and filtration tests using fine coal and silica with a medium particle size of 5 and 1.5 μm, respectively. The size of gas nuclei in natural water was estimated to be 10 μm. When forcing the water through the tip of a cavitation tube at a flow velocity above 8–15 m s^{-1}, micro-size bubbles were observed to form. Numerical simulation confirmed that, at this flow velocity, a pressure close to liquid vapour pressure was attained inside the tip of the cavitation tube, suggesting the formation of bubbles by the expansion of the pre-existing gas nuclei and subsequently filled with liquid vapours. Using a light attenuation method, the onset velocity of bubble formation by hydrodynamic cavitation was found to be dependent on the diameter and length of the nozzle, slurry temperature and initial gas content. With gas-supersaturated water, for example, the onset velocity reduced from 15 to 7 m s^{-1}. Adding frother into liquid does not affect the onset of bubble formation by cavitation, but it increases the bubble stability. Sebba has reported the formation of stable bubble swarms of approximately 25–50 μm which he called aprons, generated similarly. Adding a small amount of air into the flowing liquid stream enhanced bubble formation at a reduced liquid flow velocity, which provides a direct justification for feed aeration by hydrodynamic cavitation.

Applications of Feed Aeration

There are many new flotation devices that make use of the combined features of dispersed and dissolved air flotation. Feed slurry aeration through the concept of reactor and separator design fully exploits the combined mechanisms of bubble generation (dispersed/dissolved). Some of these flotation devices are reviewed here.

Venturi Aerated Column

The Venturi aerated column (VAC) was designed based on the concept of reactor and separator design (**Figure 2**). In this case, the reactor is a Venturi tube where air/slurry contact takes place. The separator is a column of length 1–2 m. The partial recirculation of tailings slurry was used to intensify the slurry jetting action, facilitating bubble size control (typically 500–800 μm) and bubble/particle interaction.

Figure 3 presents a direct comparison between a laboratory Denver cell and a single VAC cell in batch tests for a nickel sulfide ore. The VAC cell gave a higher concentrate grade at the same nickel recovery. Two VAC cells in series (as a rougher–scavenger configuration) were tested in an operating plant treating nickel sulfide ores. Compared to the mill rougher flotation, superior metallurgy was obtained with the VAC cells. With two VAC cells in series, similar metallurgical performance to the plant multi-stage

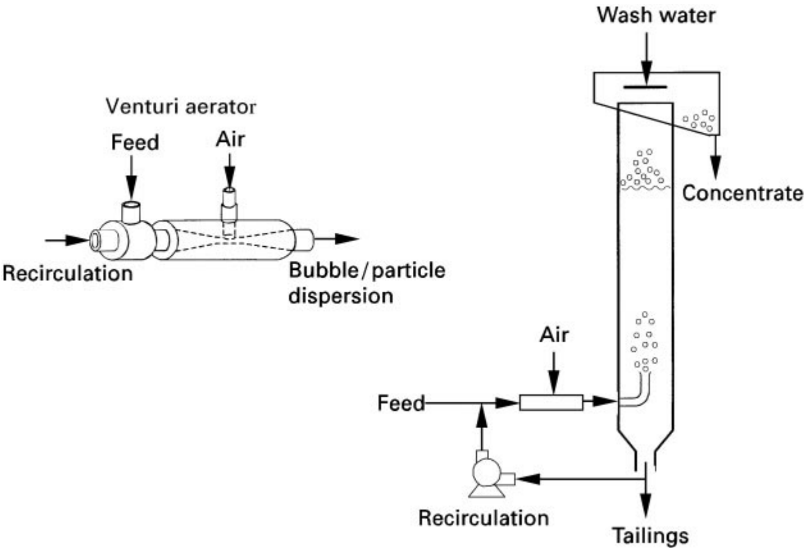

Figure 2 Schematic of a Venturi aerated column (VAC).

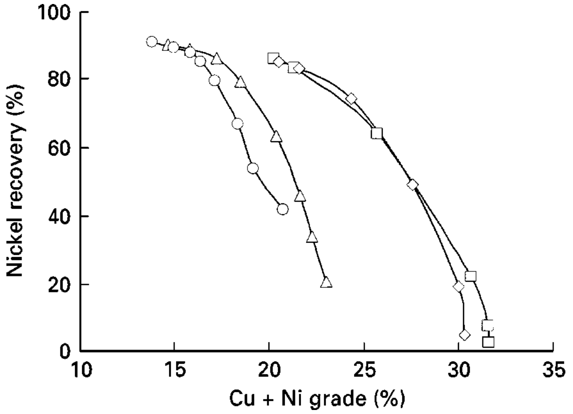

Figure 3 A direct comparison in nickel grade/recovery performance between a batch Denver cell and a batch VAC cell. Squares, column; diamonds, column (repeat); triangles, Denver; circles, Denver (repeat).

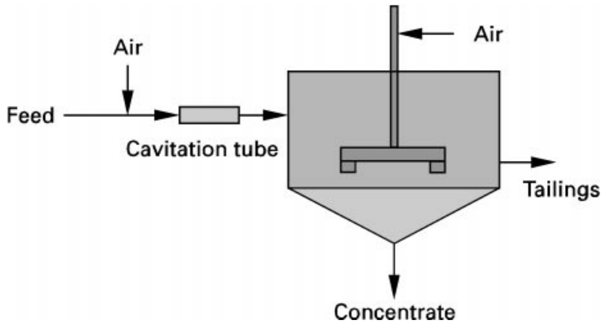

Figure 5 Schematic of a cavitation tube on the feed line before a mechanical cell.

flotation circuit was achieved, as shown in **Figure 4**. The VAC cell has also been tested and found to be successful in de-inking applications of recycled paper pulp with the performance exceeding the existing plant circuit in terms of fibre recovery at comparable brightness.

Cavitation Tube

Based on the principle of nucleation, a cavitation tube (**Figure 5**) similar to the Venturi tube was developed and tested in association with a mechanical cell. As shown in **Figure 6** for fine silica flotation (less than 5 μm), silica recovery of 30% was obtained in the mechanical cell under conventional operating conditions (no cavitation tube). By installing a cavitation tube in the feed slurry line, silica recovery was increased significantly, depending on the slurry velocity through the nozzle. The improved recovery is clearly due to the bubble formation and particle collection by gas nucleation/cavitation. Addition of a small amount of air into the feed slurry (less than 7%) before the cavitation tube further increased silica recovery, indicating that the combined mechanisms of bubble formation by dispersed/dissolved air were beneficial to fine particle flotation. In-plant testing using a similar set-up demonstrated an improved flotation performance of Cu/Ni separation.

Other Devices and Processes Using Feed Slurry Aeration

Jameson cell The innovative design of the Jameson cell is based on the point of air addition and bubble generation. It utilized the concept of reactor and separator design. The downcomer into which air is aspirated and particle collection occurs is the reactor, while the cylindrical tank is the separator. The feed under high pressure is introduced at the top of the downcomer through a nozzle, producing a high speed slurry jet which entrains air into the downcomer. In

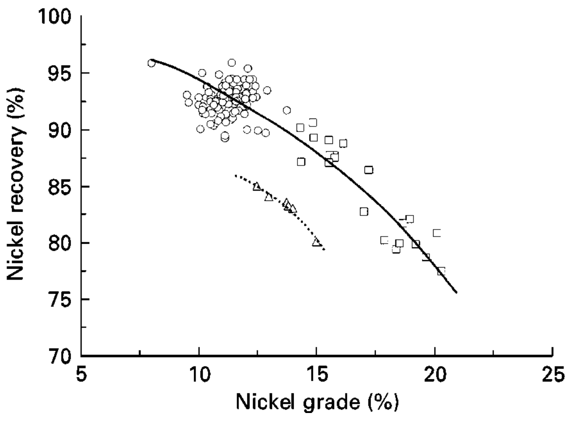

Figure 4 Comparison in nickel metallurgy between a plant rougher flotation circuit and two VAC cells in series. Squares, two VAC cells, circles, mill overall daily; triangles, mill roughers.

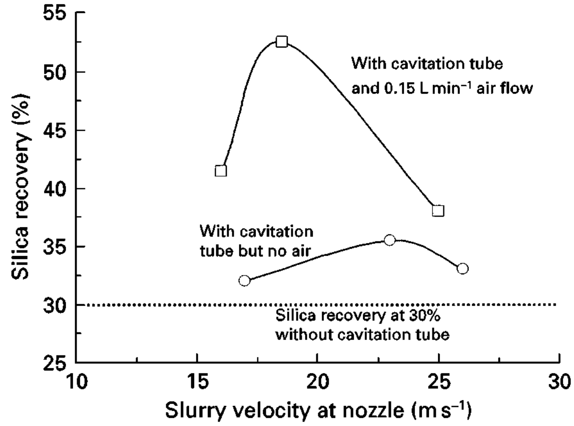

Figure 6 Fine silica recovery vs slurry velocity through the nozzle of a cavitation tube. Conditions: 1 wt.% silica (− 5 μm); 10 p.p.m. Dowfroth 250; 1.25×10^{-4} mol L^{-1} DAH; pH = 7.5–7.8; air flow rate in the mechanical cell − 2 L min^{-1}.

addition to its successful use in sulfide minerals and coal flotation, the Jameson cell has also been adopted in de-inking applications for the paper industry.

Davcra cell The Davcra cell is a type of pneumatic machine, employing feed slurry aeration. Air and feed slurry are injected into the separating tank through a cyclone-type dispersion nozzle. Air dispersion and particle collection take place in the nozzle and in the highly turbulent region in the separation tank, which is separated by the quiescent zone. A limited application has been reported.

Low energy extraction process for bitumen extraction from oil sands In bitumen extraction from Athabasca oil sands, Syncrude Canada recently adopted a low energy extraction process with hydrotransport of oil sand slurries. Oil sand slurry is transported from the mine site via pipelines (3–5 km) with a relatively high slurry velocity (4 m s^{-1}). Air is injected into the pipelines. The aerated oil sand slurry is then introduced into primary separation vessels through a tangential entry feed well. Bitumen droplets attached to air bubbles float to the top of the remaining slurry to form a primary froth. Wash water is added under the froth to reduce the amount of solids reporting to the bitumen froth. Here, hydrotransport pipelines function as a reactor to increase the bubble–bitumen contact frequencies. This technique has been implemented in operation.

The Microcel, German Bahr's cell, rapid flotation cell, Contact cell, Centrifloat cell, and air-sparged hydrocyclone are other examples employing feed slurry aeration and the concept of reactor and separator design.

Concluding Remarks

With increased understanding of the role of aeration in flotation, a new trend in flotation machine design has been established. The selection of aeration in flotation is closely related to particle collection mechanisms and, to some extent, to operation and maintenance costs. Aeration in flotation has evolved from air dispersion using direct particle–bubble contact mechanism, to *in situ* bubble formation on hydrophobic particles by gas nucleation and cavitation in dissolved air flotation. The emerging trend is a combination of the two. The location of aeration has also been evolved from slurry aeration in a flotation vessel to feed aeration in a virtual reactor followed by flotation separation in a separation tank.

Flotation is an energy-dependent process and, like all the subprocesses – solid suspension, aeration, particle–bubble interaction and bubble formation – are energy-dependent. Part of the energy dissipation in flotation systems can be attributed to the method of aeration. Ideally, as much of the input energy as possible should be directed to the main function of flotation: particle collection by bubbles. Feed aeration is associated with significant energy dissipation efficiency as the input energy is distributed evenly in slurry in contrast to mechanical cells, in which the energy is concentrated in the impeller region. The energy used for pumping, on the other hand, is a major energy requirement not needed in the existing collection processes. With the concept of feed aeration, pumping energy is utilized to force feed slurry through a hydrodynamic cavitation tube (or a Venturi tube), which facilitates the *in situ* generation of bubbles on hydrophobic particles. It is an exciting design challenge to develop energy-efficient feed aeration flotation systems.

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Reagent Adsorption on Phosphates

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Introduction

Adsorption of surfactants on minerals is the basic process governing flotation. It is controlled by various physicochemical processes in the pulp involving interactions among the mineral particles, surfactants, dissolved inorganics, solvent species and other additives such as polymers. Adsorption can be considered as selective partitioning of the surfactant adsorbate into the interfacial region, resulting from the more energetically favourable interactions between the adsorbate and the solid than those between the former and the species in the bulk solution. The interactions leading to adsorption include chemical bonding, electrostatic interaction, desolvation of the surfactant polar group and the mineral surface species, hydrogen bonding, van der Waals interactions, etc.

Water chemistry plays an important role in the adsorption process by affecting the surfactant–solution equilibria, the mineral–solution equilibria and subsequently the interactions between the surfactants and the mineral particles. The interactions in mineral–solution system include dissociation, micellization and precipitation of the surfactant, dissolution of a small amount of solids followed by hydrolysis, complexation and precipitation of the dissolved species, and the interactions between dissolved mineral species with surfactant in the bulk in various forms. The dissolved species, including those introduced due to dissolution from all the minerals present in the ore and those from the water source, fresh and recycled, are the major elements that affect the water chemistry. While impurities introduced from water can be controlled to some extent, the chemical species released into the system due to dissolution from the minerals cannot be avoided. In systems containing soluble or sparingly soluble minerals where the extent of dissolution is markedly higher than that in most oxide/silicate systems, the effect of dissolved mineral species can be drastic. Understanding the mineral–solution–surfactant chemical equilibrium under different physicochemical conditions is critical for developing reagent and processing schemes for separation.