Civil Engineering and Material of Construction

The final column design must be site-specific. There may be height and/or area considerations due to restrictions of space, and weight and loading considerations due to foundation requirements. In addition, some environmental considerations such as wind load, earthquake zone and rainfall intensity will affect steel thickness, foundations and attachments, braces and access platforms. As columns are normally much taller than mechanical flotation cells, they are often located outside, and these factors can play an important role in column design. There are also process considerations like per cent solids, wear factors, chemical composition of the slurry (pH, etc.) and particle size distribution which affect the physical structure, pipe sizing and materials of construction. In special cases, these units may be designed as pressurized vessels or as enclosed systems.

For example, many oil–water separation columns are pressurized or some installations use circulating inert gases to minimize oxidation. When columns are installed for oil–water separation duties, mainly on offshore platforms, a circulating hydrocarbon gas (propane) is often used instead of air.

Conclusions

Despite its simple design, the scale-up and modelling of column flotation is a complex problem. It includes analysis of three-phase three-dimensional flow in collection and cleaning zones and in the washed thick froth layer. In the last few years, a technique for column design has been developed. Its adequacy has been confirmed by many columns installed worldwide for a wide range of mineral and other applications.

Special attention should be paid to the carrying capacity of air bubbles and to secondary upgrading in the froth.

Design of air-sparging systems, feed distributors and also froth discharge systems is critically important for successful column operation.

Unconventional design and use of pre-aeration systems are the main trends in flotation column development at present.

See also: **II/Flotation:** Column Cells.

Further Reading

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Historical Development

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Flotation is a versatile, surface wettability-based separation process, usually taking place in an aqueous medium. In flotation, a water-repellent (hydrophobic) target to be separated is attached to a carrier lighter than the medium in which separation occurs. The target varies from fine particulates (solid or liquid) to ions and molecules, while the most commonly used carriers are air bubbles due to their ready availability, easy handling and very low cost. Compared to other light fluids (e.g. paraffin oil), air has the highest hydrophobicity, and its low density facilitates mass transfer of bubble-target aggregates from the bulk medium to the interface where froth forms and is collected/removed. Flotation was practised around a century ago, mainly for mineral separation applications. It is difficult, if not impossible, to pin down who should be given credit for the

Table 1 Key stages in flotation process development

Year	*Concept introduced*	*Inventors*
1860	Oil as a carrier	Haynes
1901	Gas as buoyant medium	Potter/Froment
1902	Ultraflotation/carrier flotation	Cattermole
1905	First generation flotation machines	Hoover
1908	Frother (organic compounds)	Higgins/Sulman *et al.*
1912	Activator ($CuSO_4$ for sphalerite)	Bradford
1913	Depressants (SO_2 for activated sphalerite)	Bradford
1925	Modern flotation collectors (xanthate for sulfides)	Keller

development of the flotation process in the various key stages. Nevertheless, **Table 1** provides a general picture of how flotation has evolved since its first applications in mineral processing.

As shown in this table, up until the 1930s all the ingredients required for selective flotation had been proposed, including: (i) a collector to render target particles water-repellent by its adsorption; (ii) a frother to stabilize bubbles and promote foaming; (iii) an activator to induce or enhance collector adsorption on target particles; and (iv) a depressant to destroy collector adsorption on unwanted particles; along with bubble generation in a flotation machine.

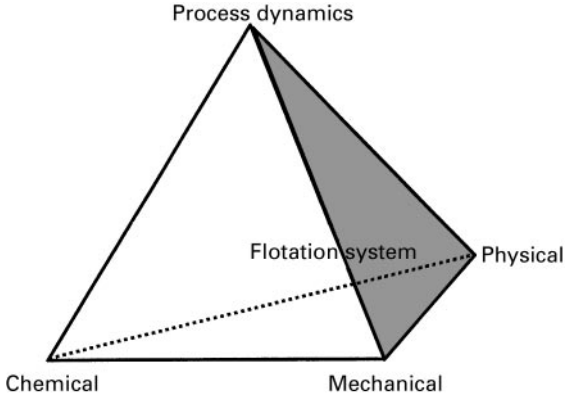

Figure 1 A flotation system shown as a tetrahedron with chemical, mechanical and physical aspects as the foundation through which process dynamics is modelled and controlled. The triangular base plane emphasizes the interrelated nature between the three foundation elements. The chemical aspect involves control of chemistry at air– and solid–aqueous interfaces by collectors, depressants, dispersants, activators, bacteria and frothers; the mechanical aspect concerns energy dissipation for bubble generation, particle dispersion, surface cleaning, hydrodynamic forces and bubble–particle contact; the physical aspect deals with the wetting phenomena and the nature of interactions between bubble–particle, bubble–bubble and particle–particle pairs in aqueous solutions involved in a flotation system.

These ingredients form one of the three foundations on which a flotation system is built. This is shown in **Figure 1** as flotation chemistry. Although neither the principles involved in flotation nor these basic ingredients have been changed since, the technology along with the fundamental understanding of the processes have evolved greatly. Developments in each of these three foundations are summarized in this article with emphasis on recent advances.

Flotation Chemistry

The search for new flotation reagents for various mineral separation systems has been one of the major aims in flotation chemistry development. Although xanthate, first used more than 70 years ago, remains the principal collector for sulfide mineral flotation, long chain surfactant has been introduced as the collector in oxide, silicate and sparingly soluble salt mineral flotation systems. The early trial-and-error approach in screening and searching for a new flotation collector has evolved into today's scientific design. Using quantum chemistry and electron density calculations, the structures of highly selective collectors have been proposed. A surfactant, with oxygen and nitrogen as the binding elements in its functional group (e.g. hydroxyoximes), was found to be a powerful and more selective collector for oxide minerals, while those with sulfur and nitrogen as the binding elements (e.g. thionocarbamate) is particularly selective for sulfide minerals. A common feature of these new collectors is their electron donor character, forming a five- to six-member closed ring structure with surface metallic elements. Many five-membered heterocyclic compounds (e.g. oxazole- or thiazole-based collectors) have recently been found to be of special selectivity in base metal ore flotation. A general correlation between flotation performance and collector chain structure (e.g. short versus long, single versus double, straight versus branched, single bond versus double bond, paraffinic versus aromatic, etc.) has also been established and a detailed list of newly developed collectors was compiled by Nagaraj in 1988. The use of a collector mixture has shown improved collecting power and selectivity, and warrants further development.

The invention of a water-soluble frother by Tveter (a polypropylene glycol ether, known as Dowfroth) was considered to be one of the major advances in frother development. Following the advent of various types of synthetic, propylene-based frothers, the effort in frother development has been directed to establishing a correlation between frother structures, frothing characteristics and their effect on recovery and selectivity. To this end, increasing branching

in frother molecules has been identified as increasing flotation selectivity, often at the cost of reduced recovery. The use of mixed frothers in a flotation system to generate air bubbles with a wide range of sizes, each suitable for particles of a given size range, has also drawn considerable attention. An increased overall recovery has been demonstrated by using a mixture of 1 : 1 polyglycol : methyl isobutyl carbinol (MIBC) as compared to a single frother at the same total concentration level. The synergistic effect of a collector and a frother on bubble-particle collection has also been recognized, although the practical application has not gained its fair share of attention. The stabilization of air bubbles by simple inorganic electrolyte should not be overlooked. Developed in the early 1930s for natural hydrophobic coal flotation without using a frother, salt flotation provides a different avenue for recovering natural hydrophobic minerals, as the surface active frother tends to adsorb on natural hydrophobic minerals with unfavourable orientations for flotation, consuming added chemicals and reducing their floatability. In 1995 Weissenborn and Pugh confirmed that the hydration shell around the added inorganic (ionic) species or frother's polar groups is responsible for froth stabilization.

Development in the activator appears rather limited, although most of the positively charged metal hydroxy species have been found suitable for activation in silicate flotation. In sulfide flotation, copper sulfate remains the only activator extensively used today. In contrast, development in depressants has taken on a different pace. Shortly after the introduction of sodium dichromate (for PbS) and SO_2 (for ZnS) in 1913, sodium cyanide (1922) and alkali sulfites (1923) appeared to be the popular depressants to use and remain the major depressants in modern sulfide flotation plants. Meanwhile, sodium silicate (1928) and macromolecular starch (1931) have become important depressants/dispersants in oxide, silicate and sulfide flotation systems. In addition to nonionic dextrins, cationic polysaccharides and anionic carboxymethyl cellulose have been found to be effective depressants because of their multi-anchoring nature with mineral surfaces. Recent efforts have been directed to the search for polyamines, which are effective in iron sulfide depression, driven by the environmental pressure of reducing SO_2 emission from smelters. Combined with SO_2, diethylenetriamine (DETA) has been found effectively to depress the pyrrhotite in pentlandite flotation, although the depression mechanism remains to be identified.

The control of the mineral surface property by biotreatment is an emerging area and represents a special branch in flotation reagent development. This approach is of special importance for desulfurization in coal flotation, selective depression in base metal sulfide flotation and hydrophobization of nonsulfide minerals. The success of biotreatment in these systems lies in the extremely high selectivity of bacteria, such as *Thiobacillus*(T-)*ferrooxidans*, towards the oxidation of pyrite, without any adverse effect on the flotability of coal, resulting in a high desulfurization efficiency in coal flotation. Also reported is an improved floatability of sphalerite by pretreatment of T-ferrooxidans in an acidic medium. However, a high dose of T-ferrooxidans has been found to be detrimental to sphalerite and galena flotation. Although sulfate-reducing bacteria have a minimal effect on the floatability of molybdenite and galena, they have been found to depress the floatability of chalocopyrite and sphalerite, resulting in highly selective flotation. Brunet *et al*. (1998) reported that the combination of T-ferrooxidans, T-thiooxidans and *Leptospirillum* accelerated pyrite oxidation. The high selectivity of a bioprocess warrants the rapid growth of biotreatment in mineral flotation.

Accompanying the development of various flotation reagents is the recognition of surface reactions/adsorption and the understanding of collector/mineral interactions in selective flotation. The theory of sulfide flotation with xanthate family collectors has advanced from simple surface chemical reactions to a generalized electrochemical–chemical process. Recognizing the electrochemical nature of collector adsorption on sulfide surfaces was a quantum leap in sulfide flotation chemistry. The application of the mixed potential theory to a sulfide flotation system provides a scientific explanation for a required oxygen level to induce the floatability, and accounts for the role of pulp electrochemical potential (Eh) in sulfide flotation for a given collector chemistry. An important consequence of electrochemical involvement in sulfide flotation is the development of self-induced (also known as 'collectorless') flotation by either controlled oxidation or sulfidization of pre-oxidized sulfide minerals. The use of cyclic voltammetry allows a direct correlation between collector adsorption (determined by charge integration), under a given applied electrode potential, and contact angle, which in turn determines the floatability of sulfide minerals. An important outcome from electrochemical studies is a new mechanism for differential flotation of complex sulfides by pulp potential control. However, the controversy regarding the collector reaction product on sulfide minerals is yet to be resolved. To this end, modern spectroscopic methods are useful. Surface reactions have been studied extensively using various surface analytical techniques, including: (i) Fourier transform

infrared spectroscopy (FTIR in both *in situ* and *ex situ* modes); (ii) Raman spectroscopy; (iii) Auger and X-ray photoelectron spectroscopy (AES and XPS); (iv) fluorescence spectroscopy; (v) electron spin resonance spectroetry; (vi) laser ionization mass spectrometry (LIMS); and (vii) time-of-fight–secondary ion mass spectrometry (TOF-SIMS). For example, the monolayer formation of polysulfide as a sulfur oxidation product on PbS has been confirmed from synchrotron XPS characterization. However, whether or not polysulfide is responsible for collectorless flotation remains to be established. Following the pioneer work on *in situ* spectroelectrochemical characterization of sulfide flotation chemistry by Leppinen *et al*. in 1988, the development of a spectroelectrochemical cell (**Figure 2**), combined with polarized FTIR spectroscopy, sets up an entirely new direction for sulfide flotation chemistry research. Using polarized infrared radiation, the orientation of the adsorbed molecular species can be derived, as shown in **Figure 3**. However, further research efforts are required to quantify the molecular orientation and to derive its practical implications in sulfide flotation practice.

In oxide and silicate mineral flotation, the interaction (i.e. adsorption of the collector, mostly surfactant) has been generally considered to be electrostatic rather than chemical in nature. An electrostatic interaction model has proven satisfactory when applied to silica and alumina flotation with ionic collectors of opposite charges from the surfaces. Progress has been made in predicting the point of zero surface charge, based on the minimum solubility theory and the sign of surface charge from the hydration energy of lattice ions. A more quantitative description of surface charge distribution has been made possible following the development of the surface triple-layer model in combination with the surface site-binding theory. Early adsorption studies have revealed the formation of surfactant hemimicelles on mineral surfaces at a bulk surfactant concentration of approximately one-hundredth of its critical micelle concentration (cmc). The formation of ionomolecular complexes has been found to enhance the floatability of oxides.

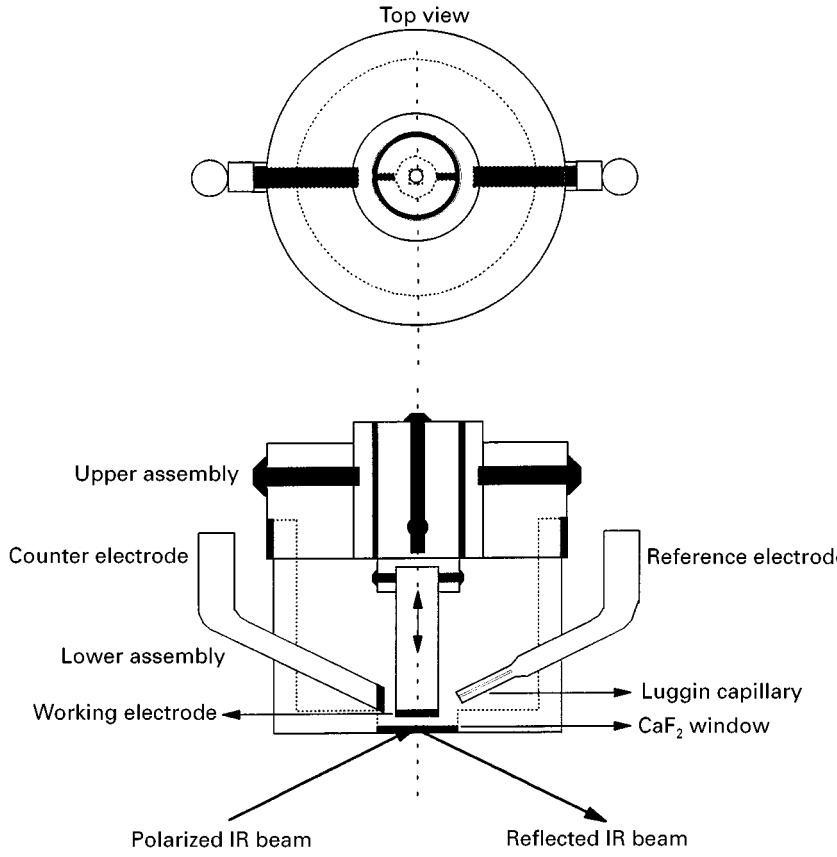

Figure 2 Schematic diagram of an *in situ* spectroelectrochemical cell suitable for studying sulfide flotation chemistry. Pushing a movable sulfide mineral working electrode against the CaF_2 window with a screw type of mechanics ensures not only elimination of bulk water films to increase the sensitivity of infrared spectroscopy, but also reproducible positioning of the electrode (after each electrode polarization) for quantitative analysis. The use of polarized infrared radiation in external reflectance mode allows identification of molecular orientation.

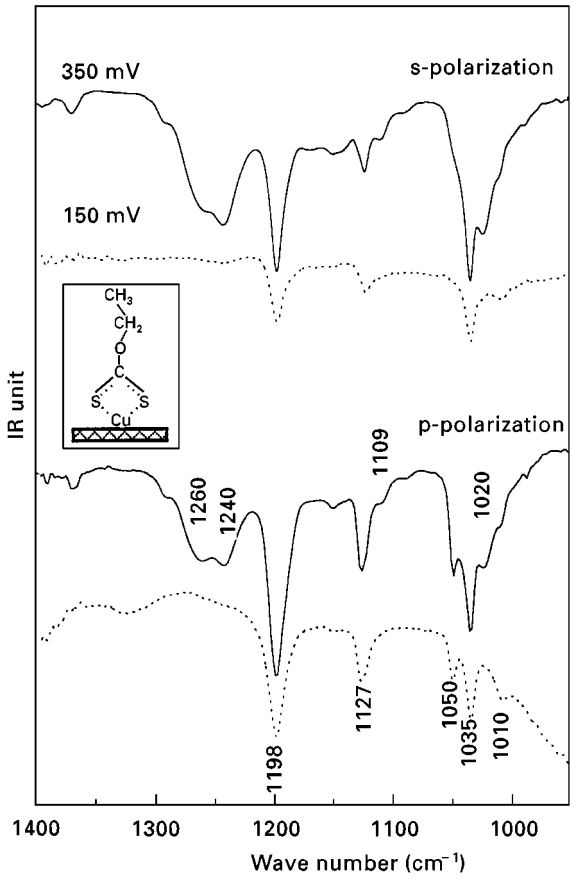

Figure 3 *In situ* infrared spectra obtained with a copper electrode polarized under electrode potentials of 150 (dotted lines) and 350 (continuous lines) mV/SHE (standard hydrogen electrode) in 2×10^{-3} mol L^{-1} potassium ethylxanthate solutions. By comparing the spectra obtained with s- and p-polarized infrared beams, a near perpendicular orientation of adsorbed copper xanthate on copper electrode (inset) was derived to account for the absence of the band at 1050 cm^{-1}, associated with COC molecular vibrations, with the s-polarized infrared beam. In contrast, a random orientation of dixanthogen, formed under a higher applied electrode potential, was ascertained by a similar spectral feature of characteristic dixanthogen bands obtained with both polarization modes.

This is consistent with recent observations on enhanced hydrophobicity of mica surfaces in a mixed cationic amine and neutral alcohol surfactant solution. The increased overall surfactant adsorption density at the solid–liquid interface is accounted for by screening elecrostatic repulsion between adjacent surfactant head groups.

Recently, a detailed study using a well-defined basal plane of crystalline sapphire in a surface forces apparatus showed that the formation of monolayer hemimicelles requires a near-cmc surfactant concentration in the surface region, while its bulk concentration has to be well below the cmc. Based on the well-known Stern–Grahame equation, this condition cannot be satisfied in the absence of any attractive driving force of electrostatic and/or chemical nature required to preconcentrate the surfactant in the surface region to the cmc level. As a result, the lack of hydrophobic monolayer formation and hence effective flotation is anticipated.

Clearly, effective oxide flotation requires creation of a chemical environment that maximizes the surface concentration of the surfactant at as low a bulk concentration as possible. Changing suspension pH to control surface charge density in oxide flotation serves as an excellent example. Under certain circumstances, activation by hydrolysed metal ions, which provide the linkage between an anionic collector and a negatively charged mineral, is necessary to induce floatability. It should be noted that the selectivity of separation in oxide flotation is relatively poor if the electrostatic force is the only driving force for collector adsorption. This is particularly true in fine particle flotation, as heterocoagulation between different minerals often induces a secondary locking which destroys the selectivity. To this end, searching for collectors which chemically anchor on to targets remains the focus in oxide flotation systems. For sparingly soluble mineral flotation, solution chemistry calculation has been proven to be one of the most valuable tools in searching for separation windows. Since bulk solution chemistry controls the flotation response, a bulk precipitation followed by surface deposition, with a switch-on type of adsorption characteristics, has been considered to be the most favourable mechanism in flotation of soluble-type minerals, where the monolayer adsorption is hardly recognizable.

A recent trend in laboratory studies of sulfide flotation chemistry is to use a mixed mineral system. With this approach, an enhanced xanthate adsorption on anodic minerals by galvanic contact of dissimilar minerals was revealed. Also derived from this type of research is the depression of pyrite by copper sulfate addition in a sphalerite/pyrite mixed mineral system, shown in **Figure 4**, as opposed to pyrite activation in a single mineral system. A similar approach has been used in oxide and salt-type flotation systems.

In summary, our understanding of the interaction mechanism of collectors with minerals in a flotation system has evolved significantly following the development of modern instrumentation. Future advances in the fundamental understanding of flotation systems are anticipated with the introduction of the atomic force microscope in mineral flotation research. A combination of electrochemistry, *in situ* spectroscopy and surface imaging at a molecular level will enable us to pinpoint the mechanism and roles of collector–mineral interactions in flotation.

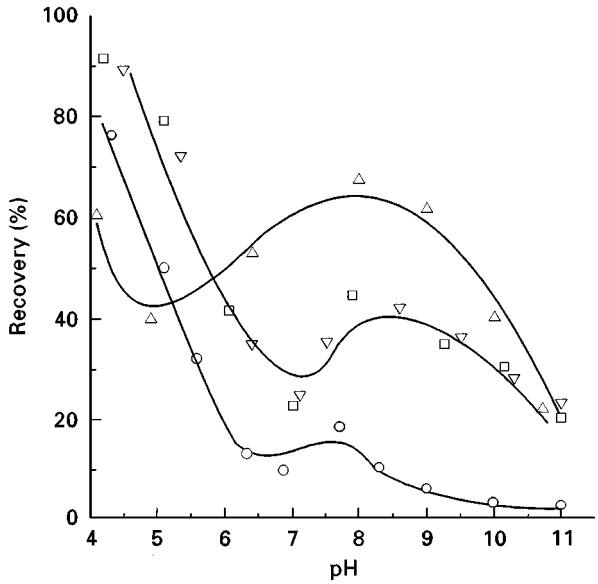

Figure 4 Flotation recovery of pyrite in the presence of 10^{-5} mol L^{-1} iso-propylxanthate alone (squares) or with cupric ions (triangles), sphalerite (inverted triangles) or both (circles). The flotation of pyrite was depressed by a combination of cupric ions and sphalerite, although cupric ions alone activated pyrite flotation, illustrating the importance of studying flotation chemistry with mixed mineral systems in the context of the separation practice.

Flotation Mechanics

Bubbles are an indispensable component of froth flotation. Bubble generation in flotation machines forms the second foundation of a mineral flotation system. It is interesting to note that the development of flotation machines follows the evolution of bubble generation methods, although a flotation machine has to fulfil three basic functions: (i) generation of sufficient amount of bubbles with suitable sizes (*c.* 0.5–2 mm); (ii) dispersion of solid materials; and (iii) effective collision between particles and bubbles, in addition to providing a quiescent zone for froth formation. **Table 2** summarizes the major steps in the early stages of flotation machine development. Up until 1911, all available bubble generation methods had been practised in flotation machines. Driven by an increased demand for metals and a need for cost reduction, the development of flotation machines in the subsequent 50 years was directed to the design of large volume cells, with the benefits of flexible process control and reduced capital cost, plant space, specific power and maintenance. Taking DO-3500 (Denver) as an example, cells of volume as large as 100 m^3 are now in operation. Radical changes incorporated in this new super-large cell include the use of a pump-type rotor, an overhung vane-type stator, a round tank of conical bottom and radial discharge of froth as in flotation columns. The most recognized development in flotation machines today is, however, the commercialization of flotation columns, followed by various innovative designs of aeration systems to generate microbubbles in response to slow flotation kinetics of fine particles.

Table 2 Early developments in bubble generation and flotation machines

Year	*Methods of bubble generation*	*Flotation acromy*
1904	Electrolysis	Electroflotation
1904	Pressure reduction	Vacuum flotation
1905	Air dispersion by agitation	Mechanical cell
	Pressurization/pressure release	Dissolved air flotation
1911	Air dispersion by spargers	Pneumatic cell

The success of conventional flotation columns initiated a surge in the development of novel flotation devices, some of which are summarized in **Table 3**. Detailed analysis of these new devices shows a common feature – the generation of fine bubbles online with high energy dissipation (e.g. high turbulence in fluid). Major advances in these devices are illustrated, for example, in a fast flotation column, shown in **Figure 5**. The in-line generation of fine bubbles (feed aeration) by either a static mixer or a simple Venturi tube ensures a high bubble–particle collision efficiency. Partial recycling of tailings to the feed allows fugitive valuables to be captured, while a deep froth with wash-water addition cleans up entrained unwanted gangues. Essentially, a flotation column in this configuration is equivalent to a flotation circuit: (i) a rougher in the middle; (ii) a cleaner on the top; and (iii) a scavenger at the bottom.

The improvement of froth quality, by deep froth and froth washing in the flotation column, brought the recent development of Outokumpu's HG tank, which features an adjustable booster cone to control froth quality. A hidden feature in these newly designed flotation devices is the role of hydrodynamic cavitation. The importance of hydrodynamic cavitation in flotation is the complete elimination of the bubble–particle collision step, resulting in a 100% increase in flotation rate constant, seen in a case study using the set-up shown in **Figure 6**. The preferential nucleation of bubbles on hydrophobic particles is anticipated to contribute to improvement in flotation selectivity. With hydrodynamic cavitation, strong mechanical agitation, which is otherwise required to provide the kinetic energy necessary to overcome energy barriers for bubble–particle attachment, can be minimized. As a result, a more quiescent environment is created for enhanced froth-pulp disintegration. Along the same line of thinking, the use of

Table 3 Examples of new flotation devices developed in the minerals industry since the 1980s

Device	*Features*	*Inventors*
Air-sparged hydrocyclone	Centrifugal force/porous cylinder aerator	Miller
Pneumatic cell	Slot aerator under pressure	Bahr
Packed column	Unlimited froth height	Yang
Microcell	Static mixer/tailing recycle	Yoon
Jameson cell	Self-aspiration: plunging slurry jet	Jameson
Contact cell	Feed aeration	Amelunxen
Ken Flote	Conditioning with dissolved air	Parekh *et al.*
USBM rapid cell	Static mixer	Jordan *et al.*
Rapid flotation column	Feed aeration/tailing recycle	Xu *et al.*
Next generation	Hydrodynamic cavitation	Zhou *et al.*

ultrasonication or vibroacoustic modulation, to facilitate gas nucleation and bubble–particle attachment, has been tested. A gas nucleation mechanism, most likely by hydrodynamic cavitation with innovative engineering of the cavitation tube or ultrasonic modulation, is anticipated to be the main feature of the next generation of flotation devices. A reactor–separator design as seen in Figure 5 is desirable to optimize individually bubble–particle contact and bubble–pulp separation.

Flotation Physics

It is evident that, for effective flotation, the thin liquid films between an air bubble and a target have to be thinned and ruptured (film stability), while association between different species (hetero-coagulation) needs to be avoided to separate one species from another. The physics of the flotation system (i.e. surface forces between various phases) controls such phenomena as thin film stability and coagulation. As a macroscopic process, flotation is often analysed in terms of micro subprocesses and the knowledge about them would serve as an encyclopedia of colloidal science. Fundamental studies in flotation physics have evolved, to today's role of hydrophobic forces in flotation, from pioneer work by Wark (capillary forces), Sutherland (contact angles), Derjaguin (interparticle forces), Derjaguin and Dukin (elementary stages of flotation), Klassen (role of hydration shells in flotation), Scheludko (thin film stability) and Schultz (hydrodynamic forces).

The capillary phenomena confirmed the existence of relatively short range molecular forces, manifested in observed surface tension. The floatability of minerals has been frequently correlated to contact angles of solid against water (or, more precisely, contact angle hysteresis in flotation practice, which involves

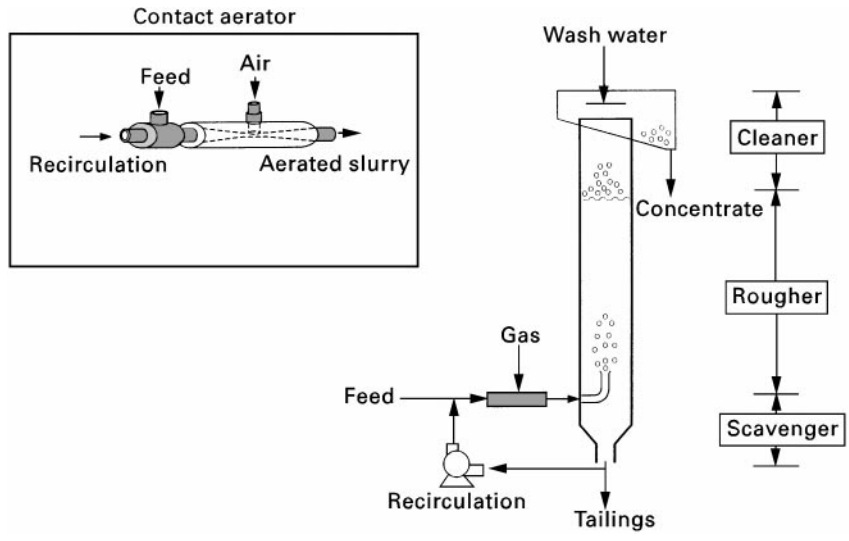

Figure 5 Schematic of a modern flotation column featuring feed line aeration (insert) and partial recycle of tailings. The main thrust of a column in this configuration is its equivalence to a virtual flotation circuit with the capability of generating fine bubbles for fine particle flotation.

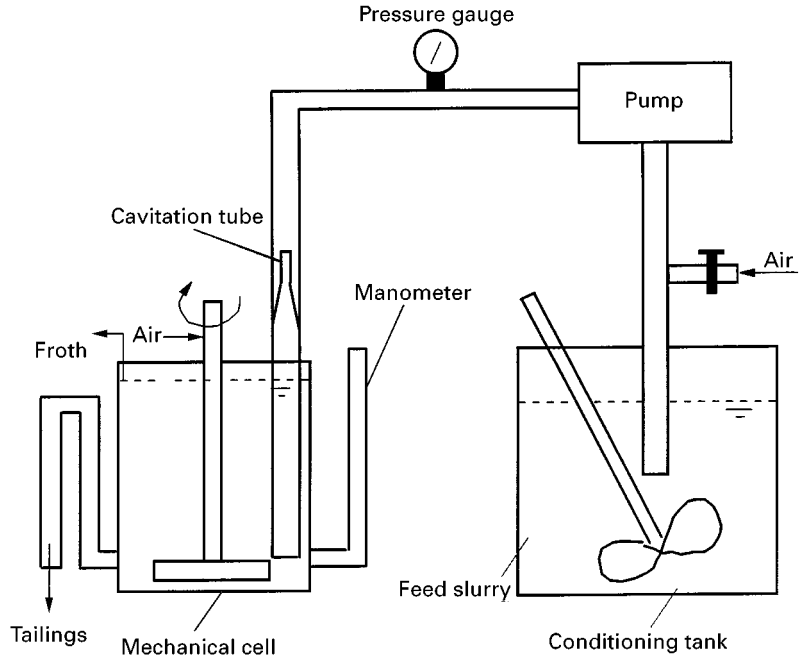

Figure 6 Schematics of a flotation system with reactor–separator design exploiting hydrodynamic cavitation in fine particle flotation. A 10-fold increase in removal efficiency of fine oil contaminants in the soil-washing process has been demonstrated in a laboratory-scale test. Using the setup at INCO's Matt separation site (Sudbury, Canada), a doubling of the pentlandite flotation rate at a comparable concentrate grade was obtained. The main attraction of this configuration is that it can be readily implemented in the existing flotation circuit by simply bridging the conditioning tank with mechanical cells using a cavitation-type reactor.

consideration of both adhesion and detachment). The contact angle phenomena manifest the competition for water molecules by solids and by water itself, assuming that the interaction between air and other phases (solid or water) is negligible. The work of cohesion of water greater than the work of water–solid adhesion is equivalent to a contact angle greater than zero as the thermodynamic criterion of floatability. However, the former provides insight into the competition between various phases. Analysis on work of adhesion and cohesion for a flotation system has contributed to the improved understanding of flotation physics. To this end, the concept of critical surface tension proposed by Zisman was adopted in a so-called Gamma flotation process, although its practical application has been limited to coal flotation or the recycling of low surface energy polymeric materials. The role of collector adsorption in flotation is to reduce the work of adhesion of target solids by exposure of weakly interactive hydrocarbon tails to water. Such a system of high solid–liquid interfacial tension is thermodynamically unfavourable, making the particles floatable.

The use of the electrostatic double layer and van der Waals forces considered in the classical colloidal stability theory (known as Deryagin–Landau–Verwey–Overbeek, or DLVO theory) has been successful in accounting for the stability of some colloidal systems. It is now generally accepted that additional forces need to be considered to understand fully the observed phenomena in flotation systems. A typical example is that alumina is not floatable in the absence of surfactant, although a strong electric double-layer attraction between air bubbles and the solids is predicted. On the other hand, quartz dehydrated at a temperature above 1000°C is readily floatable without any collector, yet the classical DLVO theory would predict repulsive van der Waals and electrostatic forces between the two. It is clear that the additional force can be either attractive or repulsive, depending on the hydrophobic or hydrophilic nature of the solid surfaces.

Thanks to a recent breakthrough in measuring surface forces directly, the presence of additional long range attractive forces between hydrophobic surfaces and short range repulsive forces between strongly hydrated surfaces has been confirmed. The former has contributed significantly to comprehending the thin film rupture phenomena which occur in most flotation systems. The force between an air bubble and a solid surface has been directly measured with an atomic force microscope and results, shown in **Figure 7**, confirm the existence of additional attractive forces. It should be noted that the direct force

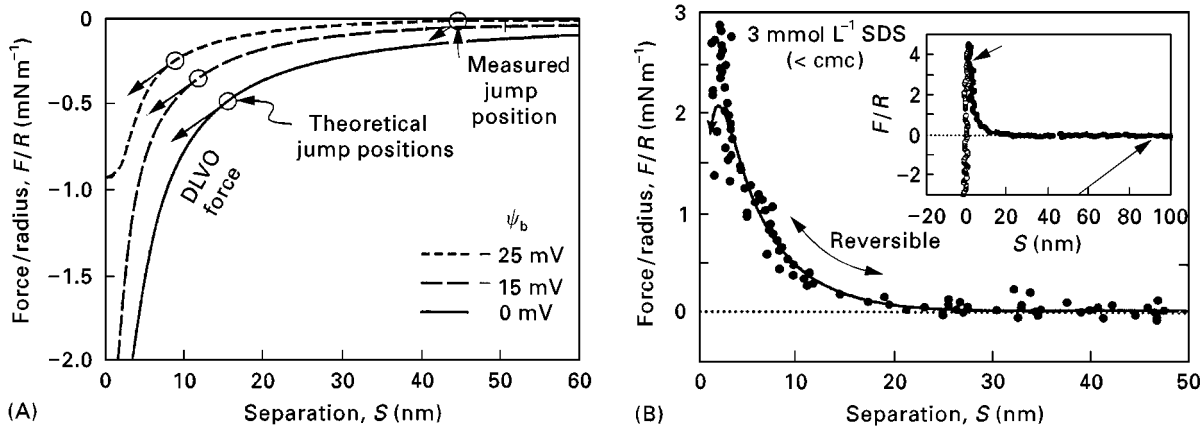

Figure 7 Forces between an air bubble and a silica particle in (A) an electrolyte solution with (B) added surfactant, measured directly with an atomic force microscope. A much greater jump in distance than predicted from the classical DLVO theory (A: shown by arrows) confirms the existence of additional attractive forces. In contrast, the presence of 3 mmol L^{-1} SDS changed the forces from a long range attraction to a long range repulsion, well-described by the DLVO theory (B), manifesting the role of surfactant in flotation.

measurement between an air bubble and a hydrophobic solid surface remains an unresolved challenge, even though it is most relevant to flotation.

Following recent advances in scientific instrumentation, such as the atomic force microscope, film balance and surface forces apparatus, flotation research has gone through a period of thermodynamic analysis of bubble–particle attachment to the understanding of intermolecular forces involved. These advances have allowed flotation subprocesses to be analysed from first principles. Bubble–particle adhesion, and hence flotation, for example requires particle–bubble contact (sliding) time greater than film rupture (induction) time controlled by wetting kinetics. An attempt has been made to derive a flotation rate equation from first principles by considering both surface forces and system hydrodynamics. The practical application of the derived equation in flotation process development remains to be explored. The empirical relations, outlined in a review by Radoev and Alexandrova (1992), remain the main source for process design and simulation.

It is important to note that chemistry, physics and mechanics, which form the three foundations of a flotation system and determine the process dynamics, are interrelated among themselves. This is emphasized in Figure 1 by a triangular relation on the base of the tetrahedron. Bubble size in a flotation system, for example, is determined by chemistry (addition of frother) which affects the physics of film stability (surface forces) balanced by mechanical forces and liquid viscosity. Only when these three factors are considered simultaneously can the flotation dynamics be optimized. An important area in flotation development is the innovations in: (i) on-stream analysis (X-ray fluorescence analyser, ash analyser, nuclear magnetic resonance and image analysis); (ii) sensors (redox, ion-selective Eh and conductivity probes); (iii) dynamic process modelling (expert systems and artificial neural networks to mimic control actions by human operators); (iv) control (fuzzy logic and self-organizing controller); and (v) instrumentation. Details on these developments are not included in this article, and interested readers are referred to the recent review articles by Sastry and Fuerstenau (1988), Mavros and Matis (1991) and the *Proceedings of the XIX International Mineral Processing Congress* (1995).

Recent Advances in Flotation Practice

It appears unnecessary to list all of the minerals processed by flotation, since almost all minerals mined today can be separated effectively by froth flotation. In addition to developments in the three foundation areas of flotation (Figure 1), significant progress has also been made in circuit design. Following the introduction of reverse, bulk and differential flotation, the multifeed circuit, shown in **Figure 8** and practised in China for processing copper sulfide, is considered to be one of the most recent advances in this regard. With the multifeed circuit, the improved recovery has been attributed largely to the autogenous carrier (piggyback) effect. The reduced reagent consumption, which creates a starving reagent addition, may have contributed to the improved concentrate grade (i.e. selectivity). In the Climax Mill (USA), the use of the multifeed circuit improved the molybdenite grade from 14 to 34% MoS_2 at comparable molybdenite recovery and

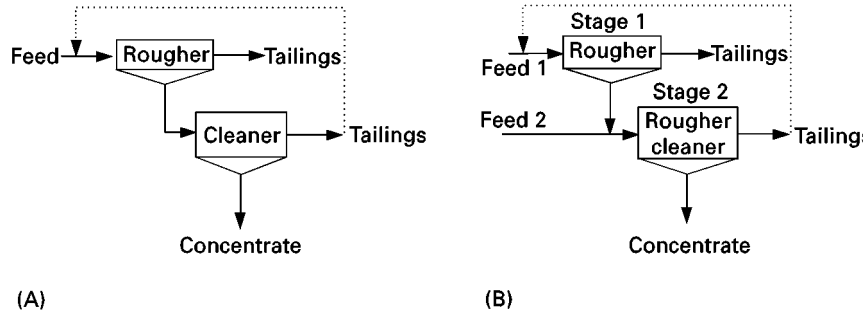

Figure 8 Comparison of (A) conventional rougher–cleaner circuit with (B) multifeed circuit. The dotted lines represent a variation of the circuits with recirculating loads. An added advantage with a multifeed circuit includes improved concentrate grade at reduced reagent consumption while maintaining the valuable recoveries.

reduced by half collector and frother consumptions. Another recent development is flash flotation which uses a coarse flotation cell (Skim-Air) in a grinding circuit to produce final concentrate from a cyclone underflow stream before further grinding (**Figure 9**). This approach minimizes overgrinding of valuable material richer in the cyclone underflow than in the feed stream. In addition to increased recovery, an improved throughput for the subsequent unit operations and the high dewatering efficiency of final concentrate are recognized with flash flotation. In tackling the challenge of fine particle flotation, high intensity conditioning has been developed. The improved process performance has been attributed to mechanical surface cleaning of slimes, shear-induced aggregation of target particles and, yet to be confirmed, *in situ* bubble formation on hydrophobized particles by hydrodynamic cavitation and resultant bubble–particle aggregation. Online pulp potential control assisted by nitrogen as the carrier gas has also been engineered in flotation machines and columns as a means of improving selectivity of sulfide mineral separation.

Concluding Remarks

With generations of research efforts, flotation has matured into a process of choice for many separation tasks, including mineral separation, bitumen extraction from tar sands, soil remediation, materials recycling, de-inking, de-oiling, de-colouring, biological species fractionation and industrial effluent detoxification in the form of either froth flotation or absorptive bubble separation. Both inventions and innovations have played an indispensable role in flotation development in an evolutionary, rather than a revolutionary, fashion. Although flotation practice has always been ahead of flotation science, the gaps

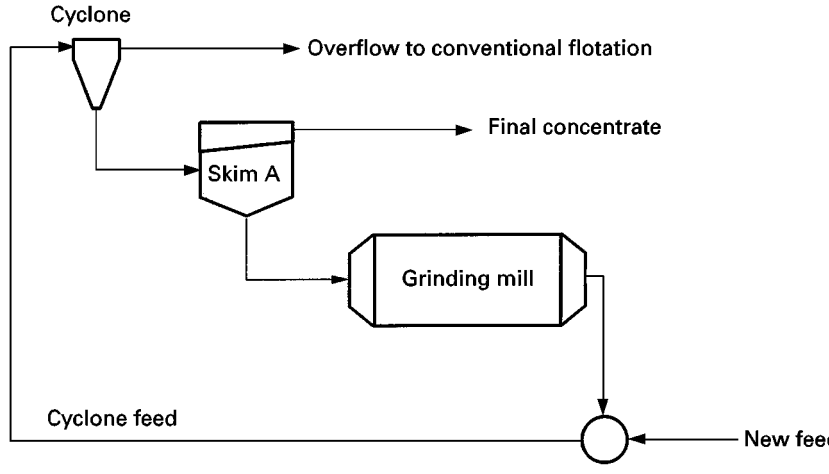

Figure 9 Schematics of a flash flotation circuit with a coarse flotation before grinding. The circuit minimizes overgrinding of valuables and improves the recovery and product quality at an increased throughput.

between the two have narrowed significantly. Improving fundamental understanding of the flotation process remains the main focus of research for the future. The areas where significant advances are anticipated include: (i) design and synthesis of more effective, environmentally friendly flotation reagents (mainly collectors, frothers and depressants); (ii) engineering of a pulp potential monitor (mineral electrodes) and control in sulfide flotation practice; (iii) development of new flotation cells to maximize separation efficiency and minimize energy consumption; (iv) understanding and utilization of biotreatment to replace both collectors and depressants; and (v) design of a better and reliable process control system based on further development of sensors and simulators. The main challenge that flotation engineers and scientists are facing is to develop viable process alternatives for fine particle flotation. Four areas of immediate interests are: (i) the development and understanding of high intensity conditioning ; (ii) hydrodynamic cavitation in flotation machines; (iii) selective aggregation by coagulation, flocculation or oil agglomeration; and (iv) practical conditions for collectorless flotation of sulfide ores.

Further research is needed in the area of flotation chemistry and implementation of the outcome into process development. All of these are driven by the depletion of rich and simple mineral resources, reduction of metal prices and the increase of environmental pressures. The processing of tailings with a gravity concentrator at Laurium, from 1864 to 1920, left tailings containing 3% lead, these were reprocessed again in 1955 by flotation with a resulting tailings assay of 0.3% lead. It is not unrealistic to suggest that the resultant tailings may be reprocessed in the future with further innovative developments, such as integration of biotreatment in flotation. To conclude, there is a long-awaited need to widen the range of flotation applications to nonmineral-processing applications, such as in material recycling and waste remediation, with revolutionary changes in flotation technology.

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Hydrophobic Surface State Flotation

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Introduction

The essence of particle separation by flotation is the creation of a hydrophobic surface state, i.e. a surface that is not wetted by water, a particle surface at which bubble attachment will occur leading to flotation due to the buoyancy of the particle–bubble aggregate. (Particle flotation can also, however, be accomplished by bubble entrapment rather than by bubble attachment. For example, entrapment of air during particle aggregation/flocculation can lead to the flotation of aeroflocs.) In many instances this hydrophobicity must be established in a selective manner, frequently by collector (surfactant) addition, so that one particle type can be separated from other particle types which are maintained in a hydrophilic state.

The extent to which a surface is hydrophobic can be described in various ways. Two of the most common laboratory methods are contact-angle measurement and bubble attachment time measurement. The contact angle measurement tends to be an equilibrium, or pseudo-equilibrium, measure of hydrophobicity, while the bubble attachment time measurement is a kinetic measure of hydrophobicity. Other measures of hydrophobicity are also possible and include bubble pick-up and microflotation experiments.