

Froth Flotation

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6.6.1 Introduction

Flotation is a process of separation and concentration based on differences in the physicochemical properties of interfaces. Flotation can take place either at a liquid–gas, a liquid–liquid, a liquid–solid or a solid–gas interface.

- ◆ For example, *oil flotation* takes place on the interface between oil and water. *Film flotation* takes place on a free water surface. In this flotation process, hydrophobic particles float on the free surface and are thereby separated from nonfloatable hydrophilic particles, which sink into the liquid phase. In *carrier flotation*, colloidal particles attach themselves onto the surface of larger particles (carrier minerals) and float together with the carrier minerals.
- ◆ In *froth flotation*, the flotation takes place on a gas–liquid interface. Hydrophobic particles, which may be molecular, colloidal, or macro-particulate in size, are selectively adsorbed or attached to and remain on the surface of gas bubbles rising through suspension, and are thereby concentrated or separated from the suspension in the form of froth.
- ◆ Many interfacial phenomena, which we have discussed in Modules 1–6, are observed in flotation. It is an interfacial separation method, as illustrated in Fig. 6.6.1.

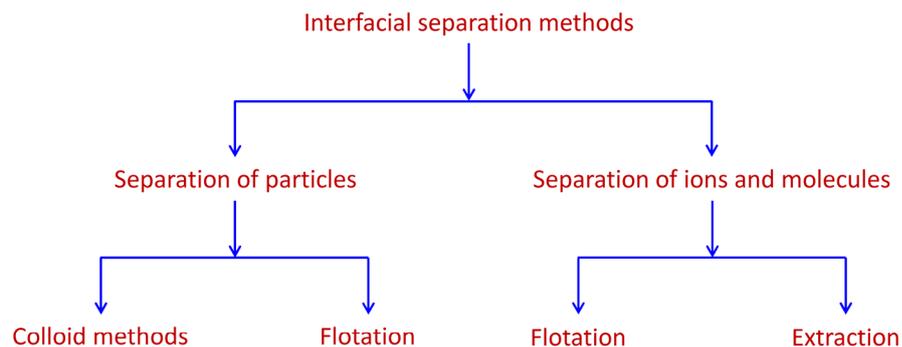


Fig. 6.6.1 Role of flotation in interfacial separation methods.

- ◆ Of the flotation techniques, *froth flotation* is the only technique that has significant industrial application. Froth flotation has been used by mineral and chemical engineers for the separation and concentration of aqueous suspensions

or solutions of a variety of minerals, precipitates, inorganic waste constituents, and even microorganisms and proteins.

- ◆ The carrier and agglomerate flotation processes have been developed to increase the kinetics of bubble–particle interaction in the fine particle flotation. Sometimes, for simplicity, froth flotation is simply termed as *flotation*. Froth flotation essentially is an application of foams. The separation process is based on the surface properties such as wettability and surface charge of the components to be separated.
- ◆ It is estimated that over two billion tons of various ores and coal are treated annually by flotation processes worldwide. The scope of flotation technology is being broadened to include other areas, such as waste paper recycling, food processing and secondary resource recovery. Today, deinking by flotation annually contributes 130 million tons of recovered paper to the worldwide paper production. Some applications of flotation separation are given in Table 6.6.1 (Schramm, 2005).

Table 6.6.1 Some applications of flotation

Species recovered	Recovered from	Industrial process or interest
Non-ferrous metal sulfides (Cu, Pb, Zn, Ni, Co, Mo, Hg, Sb)	Mineral ores	Metal production
Potassium chloride	Potash	Fertilizer
Coal fines	Ash-producing shales and rocks, and SO ₂ emission-producing metal sulfides	Electric power
Ink particles	Waste paper	Paper recycling
Silver	Photographic materials	Recycling
Copper	Acid mine effluents	Metal production
Bitumen	Oil sands	Petroleum industry

6.6.2 Flotation cells

- ◆ Flotation works efficiently only if the particulates to be floated are fully liberated (i.e., individually free particles) from the other phases. The mixture of appropriately sized and liberated particles (viz. the flotation feed) from which the selected particles are to be floated is first conditioned with the appropriate reagents. This suspension (of about 1:3 solids to water by weight) constitutes the flotation pulp.
- ◆ It is then placed and agitated using impellers in a suitable container called a *flotation cell*, as shown in Fig. 6.6.2.

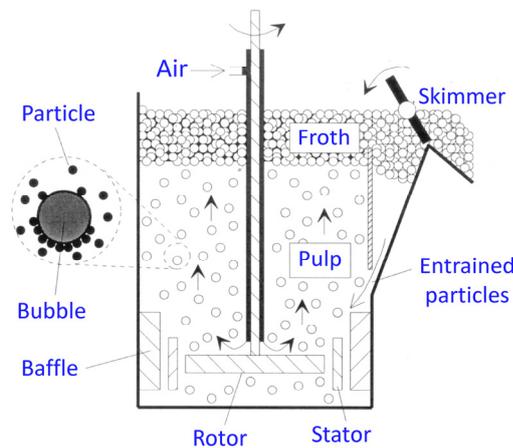


Fig. 6.6.2 Schematic diagram of an agitation-type flotation cell.

- ◆ Air is drawn in or sometimes fed into the cell near the impeller to form fine bubbles. These fine bubbles collide with the particles, attach to those particles which have the acquired hydrophobicity, and rise to the surface where they form a froth, which is removed as a flotation concentrate (a froth product) by skimming. The hydrophilic particles that are not floated with the bubbles remain in the pulp, and are removed from the cell as *tailings*.
- ◆ The typical industrial flotation cell, schematically shown in Fig. 6.6.2, is referred to as a *mechanical cell*. There are other types of flotation cells, for example, the EKOF (Erz and Kohle) flotation cell, the MicrocelTM cell, and the Jameson cell (Fig. 6.6.3). These cells are termed *pneumatic cells*.



Fig. 6.6.3 Jameson cell (photograph courtesy: M/S Xstrata Technology).

- ◆ The size of flotation cells varies from a laboratory model with a volume of about 2 dm^3 to a large commercial cell with a volume of over 200 m^3 . In a continuous flotation process, several individual cells are joined to form a multi-compartment unit, which is referred to as a *bank of cells*.

6.6.3 Collectors, frothers, depressants, activators and deactivators

- ◆ The hydrophobic and hydrophilic character of the surfaces can be changed using surfactants. A surfactant which makes the surface hydrophobic, is called a *collector* and possess at least one non-polar group. The non-polar group is usually represented by a hydrocarbon but it may be a fluorocarbon or a siloxane.
- ◆ Owing to chemical, electrical, or physical attraction between the polar groups and the surface sites, the collectors adsorb onto the particles with their non-polar groups oriented towards the bulk solution, thereby imparting hydrophobicity to the particles.
- ◆ Collectors commonly used in mineral flotation include short chain alkylxanthates for base metal sulfides, long chain amines for quartz, mica, feldspars, potash, and long chain fatty acids and their alkali soaps for phosphates, hematite, and oxidized sulfides or calcium soap in flotation deinking.
- ◆ The second role of the surfactants in flotation is to control the characteristics of the gas–liquid interface. These surfactants are often non-ionic, generally slightly soluble, monohydroxylated compounds such as cresol that are added to induce the desired froth stability during flotation and to allow the mechanically entrained

particles to drop back to the pulp phase with the draining liquid. Thus, they are popularly called *frothers*, although their frothing abilities are not always the most important characteristics. The froth is a three-phase foam that is produced when the bubbles, laden with the (selectively collected) hydrophobic particles, rise to the surface of the aqueous suspension (i.e., the pulp). The frothers strongly influence the kinetics of bubble–particle attachment.

- ◆ Flotation is possible only when the surface of the particles to be floated is hydrophobic. When the surface of the particles is completely wetted by water, they are not floated. The contact angle is an indicator of the hydrophobic character. A number of both organic and inorganic solids exhibit varying degrees of hydrophobic character when their surfaces are freshly formed. These include hydrocarbons, waxes, coals, graphite, tars, bitumen, sulfur, talc, molybdenite, printing inks and various synthetic plastics.
- ◆ In addition to the collectors and frothers, a number of inorganic and organic reagents are employed as ‘modifying’ or ‘regulating’ agents in flotation of complex multi-component ores. These ensure that some of the components are hydrophilic, or reinforce the action of a given collector. These are termed *depressants*, *activators* or *deactivators*.
- ◆ Copper sulfate is an example of activators used in the flotation of sphalerite with xanthate at relatively high pH values. This activator is effective because of its action with the collector to form compounds of low solubility products.
- ◆ Polymers such as starch can depress flotation. In this case, the decrease in flotation is achieved in spite of the increased collector adsorption by the peculiar structure of the collector–starch clathrates formed with a hydrophilic exterior.
- ◆ Cyanides are well-known deactivators used for copper and other metal ions. The cyanide ions prevent the adsorption of the collectors onto the metallic sites.

6.6.4 Role of intermolecular and surface forces

- ◆ The flotation technique can be efficiently applied only to the fine particles. For illustration, let us assume that the particle is spherical. The surface energy is proportional to the particle surface area or square of the particle diameter. The particle potential energy or body forces are proportional to the particle volume or cubic of the particle diameter.
- ◆ If the particle size decreases, then the ratio of the particle surface to volume, which is inversely proportional to the particle diameter, increases. At a given value of this ratio, the surface effects predominate over the bulk effects.
- ◆ In such a case, the conventional separation methods based on the bulk properties would not be appropriate. To separate a mineral mixture, the difference in the surface properties of the minerals must be utilized and the separation methods based on the interfacial properties, such as flotation, must be employed.
- ◆ If the particle size increases, the body forces predominate over the surface forces. Flotation separation is therefore inefficient; instead particle separation techniques based on the body forces such as gravity separation methods, are effective.
- ◆ Laboratory testing and plant practice have clearly identified approximately 200 μm as an upper particle size limit for flotation of metallic ores and up to 3×6 mesh Tyler (6.68 mm \times 3.33 mm sieve opening) for bituminous coal.
- ◆ The limiting parameter is usually dictated by the stability of the bubble–particle adhesion during the bubble rise in a flotation machine. It also depends on the bubble loading capacity, i.e., on the buoyancy of the bubble volume to levitate the mineralized bubble.
- ◆ For particles of diameter of 1 μm or less, the body forces of gravity and inertia can be neglected compared with the surface forces. The collision between particles resulting from Brownian motion (see Lecture 3 of Module 1) can lead to perikinetic coagulation (see Lecture 2 of Module 6). The properties of such suspensions strongly depend on the surface properties of the dispersed solid phase.

- ◆ For larger, but still fine particles, the collisions resulting from mixing, difference in sedimentation velocity and/or other effects due to hydrodynamic motions can lead to orthokinetic coagulation (see Lecture 2 of Module 6) that can also influence the behavior of such suspensions to a large extent.
- ◆ In flotation, the solid particles and the air bubbles are usually not as small as colloids. The flotation suspensions and froths are hardly considered to be a colloidal system. In spite of this fact, flotation is based on the phenomena and laws of interfaces, with which colloid chemistry and colloidal hydrodynamics deal. Therefore, flotation is closely connected with the colloid and interface science.
- ◆ The orders of ratios of the body forces to surface forces are given in Table 6.6.2.

Table 6.6.2 Orders of magnitude of the characteristic body to surface forces

Force ratio	Mathematical expression
$\frac{\text{Gravitational force}}{\text{Electrical force}}$	$\frac{hR^2\Delta\rho g}{\varepsilon\varepsilon_0\zeta^2}$
$\frac{\text{Gravitational force}}{\text{van der Waals force}}$	$\frac{h^2R^2\Delta\rho g}{A_H}$
$\frac{\text{Inertial force}}{\text{Electrical force}}$	$\frac{hR^5(\Delta\rho)^3 g^2}{\varepsilon\varepsilon_0\zeta^2\mu^2}$
$\frac{\text{Inertial force}}{\text{van der Waals force}}$	$\frac{h^2R^5(\Delta\rho)^3 g^2}{A_H\mu^2}$

R = radius of particle, h = close separation distance between surfaces (~ 0.2 nm at the physical contact), g = acceleration due to gravity, $\Delta\rho$ = density difference between the particle and water, μ = viscosity of water, A_H = Hamaker constant, ε = dielectric constant, ε_0 = permittivity of free space, and ζ = zeta potential

- ◆ The variation of the force ratio with the diameter of the particles is illustrated in Fig. 6.6.4.

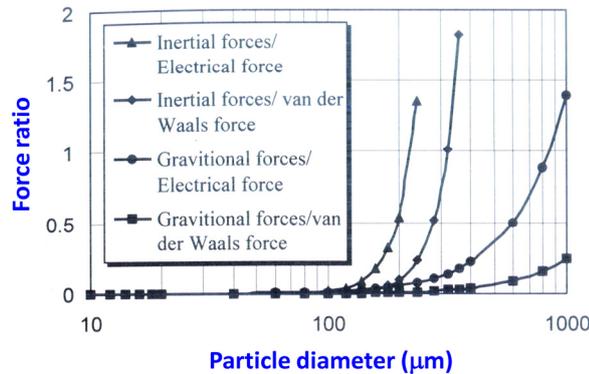


Fig. 6.6.4 Variation of force ratio with the particle diameter.

Example 6.6.1: Compute the force ratios given in Table 6.6.2 for an aqueous flotation system for which, $R = 1 \mu\text{m}$, $\Delta\rho = 3000 \text{ kg/m}^3$, $\zeta = 100 \text{ mV}$ and $A_H = 1 \times 10^{-20} \text{ J}$. Take $h = 1 \text{ nm}$. Comment on your results.

Solution: For the given aqueous system, we have,

$$\mu = 1 \times 10^{-3} \text{ Pa s} \quad \varepsilon = 80$$

The permittivity of free space, $\varepsilon_0 = 8.854 \times 10^{-12} \text{ C}^2 \text{ J}^{-1} \text{ m}^{-1}$

$$\frac{\text{Gravitational force}}{\text{Electrical force}} = \frac{(1 \times 10^{-9})(1 \times 10^{-6})^2 (3000)(9.8)}{(80)(8.854 \times 10^{-12})(0.1)^2} = 4.2 \times 10^{-6}$$

$$\frac{\text{Gravitational force}}{\text{van der Waals force}} = \frac{(1 \times 10^{-9})^2 (1 \times 10^{-6})^2 (3000)(9.8)}{1 \times 10^{-20}} = 2.9 \times 10^{-6}$$

$$\frac{\text{Inertial force}}{\text{Electrical force}} = \frac{(1 \times 10^{-9})(1 \times 10^{-6})^5 (3000)^3 (9.8)^2}{(80)(8.854 \times 10^{-12})(0.1)^2 (1 \times 10^{-3})^2} = 3.7 \times 10^{-10}$$

$$\frac{\text{Inertial force}}{\text{van der Waals force}} = \frac{(1 \times 10^{-9})^2 (1 \times 10^{-6})^5 (3000)^3 (9.8)^2}{(1 \times 10^{-20})(1 \times 10^{-3})^2} = 2.6 \times 10^{-10}$$

These values show that the gravitational and inertial forces are much smaller than the electrical and van der Waals forces for this system.

6.6.5 Flotation conditions

- ◆ Energy is needed for the bubble–particle attachment. The bubble–particle aggregate can be viewed of occurring in two steps. In the first step, energy is required to deform the bubble in order to make attachment of the particle possible. The bubble has a spherical surface. When the particle encounters the bubble, the bubble slightly deforms, which results in a larger surface area and hence in an increase in surface energy. In the second step, part of the liquid–vapor and liquid–solid interfaces is replaced by the solid–vapor interface.
- ◆ This can be mathematically expressed as,

$$W_a = W_d + \gamma_{SV} - \gamma_{SL} - \gamma_{LV} \quad (6.6.1)$$

where W_a is the energy of attachment and W_d is the energy of deformation. For flotation to occur, the bubble–particle aggregate must be stable. Therefore, the energy gain of the detachment process must be high enough and must not be overcome by external forces, i.e.,

$$W_d + \gamma_{SV} - \gamma_{SL} - \gamma_{LV} + W_d' < 0 \quad (6.6.2)$$

where W_d' is the energy of detachment. The work done by attachment is negative, and it should lead to a decrease in energy. Both the detachment work and the work of deformation are positive. This leads to the condition,

$$\gamma_{SV} - \gamma_{SL} - \gamma_{LV} < 0 \quad (6.6.3)$$

Equation (6.6.3) reflects that for flotation to occur the surface tension of the solid–vapor interface is to be smaller than the sum of surface tensions of the solid–liquid and liquid–vapor interfaces.

- ◆ Using the Young–Dupré equation [eq. (2.2.8)], the following condition, referred to as the *Zisman condition*, can be expressed as,

$$\gamma_{LV} (\cos \theta - 1) < 0 \quad (6.6.4)$$

where θ is the contact angle (see Lecture 2 of Module 2).

- ◆ The negative work of attachment depends on the contact angle, as seen from Zisman's condition, viz. if the contact angle increases, the work needed for attachment increases too. At a very small contact angle (which means near-complete wetting), flotation cannot occur. A summary of Zisman's results involving floatability, contact angle and surface tension are shown in Fig. 6.6.5.

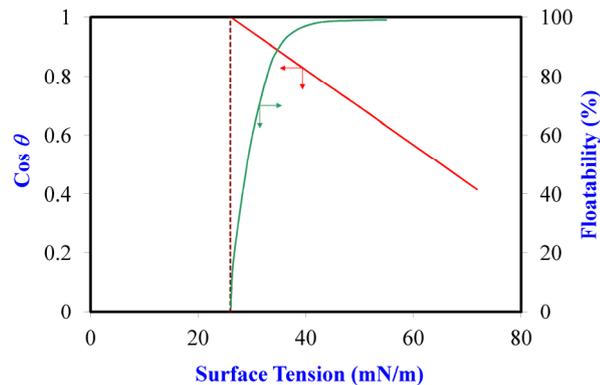


Fig. 6.6.5 Variation of contact angle and floatability with surface tension.

- ◆ According to Fig. 6.6.5, the contact angle always decreases (i.e., $\cos \theta$ increases) with decreasing liquid–vapor surface tension. Surfactants can be used to manipulate the surface energies of the liquid–solid and liquid–vapor interfaces in order to modify the contact angle. Thus, the surfactant concentration can be varied to control floatability.
- ◆ Indeed, the floatability varies with the surfactant concentration. A competition exists between floatability and stability. At low surfactant concentration, both the particle and the bubble surfaces are sparsely loaded with surfactant and the surfactant facilitates floatability.
- ◆ On the other hand, at very high surfactant concentrations, both the particle and the bubble surfaces are saturated and there is maximum stability against particle–bubble aggregation so that there is no floatability. In between these two extremes, there lies optimal floatability. This occurs when the adsorbed surfactant molecules lower the surface tension thereby minimizing the attachment energy, but the surface is not loaded too much with surfactant to prevent aggregation.

- ◆ The dynamical aspects may influence the behavior and things may differ on different timescales. The diffusivity of the surfactant molecules plays a dominant role in this situation.

6.6.6 Flotation recovery

- ◆ Liquid-flow around a bubble has an important effect on the bubble–particle interaction. Particles follow their trajectory around the bubble, attach or pushed away from the bubble again.
- ◆ A maximum angle exists, which is termed the *collision angle* (θ_c), beyond which no collision takes place, and the particles are pushed away from the surface of the bubble by the liquid.
- ◆ Below this contact angle, the particles collide with the bubble, but do not necessarily become attached to the bubble. Below a *critical contact angle* (θ_{cr}), which is smaller than the collision angle, the particles collide and attach to the bubble. Beyond this angle, the particles collide with the bubble, slide along the surface and move away.
- ◆ Due to the liquid flow, only a small fraction of the particles are able to attach to the bubble. In addition, a minimum sliding time exists, which is needed for the particles to attach.

6.6.6.1 Probability of collision

- ◆ The probability of a bubble–particle collision depends on the size of the particle, d_p , and the size of the bubble, d_b . It also depends on the liquid flow conditions (Yoon, 2000). Theoretical calculations for some well-defined flow types have yielded the following equation for the collision probability.

$$P_c = A \left(\frac{d_p}{d_b} \right)^n \quad (6.6.5)$$

where the coefficients, A and n are given in Table 6.6.3 for three different flow regimes.

Table 6.6.3 The values of A and n for different flow types

Flow type	Reynolds number	A	n
Stokes	$0 < \text{Re} < 300$	1.5	2
Intermediate	$300 < \text{Re} < 10^4 - 10^5$	$1.5 \left[1 + \frac{(3/16)(\text{Re} - 300)}{1 + 0.249 \text{Re}^{0.56}} \right]$	2
Potential	$\text{Re} > 10^5$	3	1

Re = Reynolds number of bubble

- ◆ The condition for using the values of A and n given in Table 6.6.3 is that the flow around the bubble is symmetric. In practice, flow around bubbles is always asymmetric, but the values will give an indication of the collision probability.

6.6.6.2 Probability of attachment

- ◆ Bubble–particle attachment depends largely on the hydrophobicity of particles, which means the ability of particles to adhere to the surface of the bubble. When the particles are sufficiently hydrophobic to attach to the surface, there is also still the possibility of particle to collide with the bubble surface and slide along the surface away from the bubble again.
- ◆ The probability of attachment, viz., the probability that particles collide with the bubble, slides along its surface and attaches, depends on the *induction time* and the *sliding time* of the particle, i.e.,

$$P_c = \frac{t_i}{t_s} \quad (6.6.6)$$

where t_i is the induction time (i.e., the time required to thin and disrupt the liquid film between bubble and particle), and t_s is the sliding time (i.e., the minimum contact time of particles sliding along the surface of a bubble).

- ◆ If the induction time is greater than the sliding time, particles will never be able to attach to the bubble surface.

6.6.6.3 Flotation recovery

- ◆ Probabilities of collision and attachment are important quantities to determine the collection efficiency of a flotation process. The quantity describing the efficiency of the process is termed *flotation recovery* (R). It is defined as the number of particles collected by the gas bubble divided by the number of particles in the slurry passing by the bubble. It is a quantification of the efficiency of the flotation process. The equation for flotation recovery is given by (Koper, 2009),

$$R = \frac{N_c}{\frac{\pi}{4}(d_p + d_b)^2 Hc} \quad (6.6.7)$$

where c is the particle concentration, H is a given height within which the flotation recovery is calculated, and N_c is the amount of collected particles during the traversal of the distance, H .

- ◆ The quantity, N_c , can be calculated by multiplying the probability of a particle being collected with the number of possible particle collisions (N_c^i), i.e.,

$$N_c = PN_c^i \quad (6.6.8)$$

- ◆ The probability of particle collection by a bubble (P) is dependent on the probability of bubble–particle collision (P_c), probability of adhesion (P_a), and the probability of detachment (P_d). It is given by (Yoon, 2000),

$$P = P_c P_a (1 - P_d) \quad (6.6.9)$$

- ◆ The number of possible collisions, which is the maximum number of all collected particles, depends on the diameters of bubble and the particle, and also on the rising velocity of the bubble (u) and the particle settling velocity (v) as,

$$N_c^i = \frac{\pi}{4}(d_p + d_b)^2 (u + v)c \quad (6.6.10)$$

- ◆ The flotation recovery (R) can be computed from the expression,

$$R = P_c P_a (1 - P_d) \left(1 + \frac{u}{v}\right) \quad (6.6.11)$$

Example 6.6.2: For a laboratory flotation of an iron ore in water, it was observed that 2 mg was collected while traversing 2 m of the flotation column. The concentration of the ore in water was 0.5 kg/m^3 . The average diameter of the bubbles was 2 mm and the average diameter of the particles was 0.1 mm. Compute flotation recovery.

Solution:

Given data: $d_p = 1 \times 10^{-4} \text{ m}$, $d_b = 2 \times 10^{-3} \text{ m}$, $H = 2 \text{ m}$, $c = 0.5 \text{ kg/m}^3$ and $N_c = 2 \times 10^{-6} \text{ kg}$

$$R = \frac{2 \times 10^{-6}}{\frac{\pi}{4} (0.1 \times 10^{-3} + 2 \times 10^{-3})^2 \times (2 \times 0.5)} = \frac{2 \times 10^{-6}}{3.46 \times 10^{-6}} = 0.578$$

Therefore, the flotation recovery was 57.8%.

6.6.7 Micro-processes in flotation

- ◆ If a particle indeed becomes attached to a bubble, a series of steps takes place from the particle–bubble contact until final attachment. These micro-processes can be summarized as follows.
 - (i) Thinning of the intervening liquid film on the bubble surface
 - (ii) Rupture of the film
 - (iii) Formation of a three-phase contact line and attachment
 - (iv) Detachment
- ◆ Flotation can only take place when the thin liquid film between particle and bubble is unstable. During the thinning of the film, the hydrodynamic and interfacial forces play an important role (see Lectures 3 & 4 of Module 5). The film reaches a critical thickness and then it ruptures.
- ◆ The energy required for the formation of the primary hole in the film is provided by the kinetic energy of the particles. This amount of work can be seen as the minimal energy needed for flotation to occur by creation of the first three-phase contact.

- ◆ The three-phase contact line, which is formed after attachment of the particle to the bubble, gives rise to the *formation free energy*. The formation free energy per unit length of contact line is the *line tension*,

$$\kappa = \left(\frac{\partial G}{\partial L} \right)_{T,V,A} \quad (6.6.12)$$

The typical value of line tension, κ , is of the order of 10^{-10} J/m. The change in surface free energy, dG , is given by,

$$dG = \gamma_{SV}dA - \gamma_{LV}dA - \gamma_{SL}dA + \kappa dL \quad (6.6.13)$$

- ◆ A solid–vapor interface is formed whereas a liquid–vapor and a solid–liquid interface are removed, and a three-phase contact line is formed. The capillary force at this line is (Koper, 2009),

$$\varepsilon = \frac{d(\Delta G)}{dA} = \gamma_{SV} - \gamma_{LV} - \gamma_{SL} + \kappa \frac{dL}{dA} \quad (6.6.14)$$

$$dL = 2\pi dr, \quad dA = 2\pi r dr \cos \alpha \quad (6.6.15)$$

$$\cos \alpha = \left[1 - \left(\frac{2r}{d_p} \right)^2 \right]^{1/2}, \quad \frac{dL}{dA} = \frac{1}{r \cos \alpha}$$

- ◆ From Young–Dupré equation [eq. (2.2.8)],

$$\gamma_{SV} - \gamma_{SL} = \gamma_{LV} \cos \theta \quad (6.6.16)$$

- ◆ For the contact angle, θ , one may use the dynamic contact angle (see Lecture 2 of Module 2), which is experimentally determined. It varies from the equilibrium contact angle, and also varies with the contact line motion. The contact line changes with the instantaneous radius, r . When r becomes very small, the capillary force becomes indefinitely large. Therefore, a certain critical radius, r_{cr} , is needed to make three-phase contact line expansion possible. This radius is associated with the critical amount of energy. This means that there is a minimal pore opening needed to give rise to three-phase contact line expansion.
- ◆ When a particle is attached to a bubble, different forces (e.g., gravity force, capillary force on the three-phase contact area, hydrodynamic pressure of the liquid column on the contact area, and additional hydrodynamic forces due to the

motion and mass of the particle) act on the particle, which are balanced by the buoyancy force. A repulsive force needs to be overcome before the detachment can take place.

Exercise

Exercise 6.6.1: Calculate the flotation recovery of an ore in water if the velocity of bubble is 20 mm/s and the settling velocity of particle is 10 mm/s. The probability of adhesion is 0.7 and the probability of detachment is 0.3. The diameter of the bubble is 1 mm and the same of the particle is 100 μm .

Exercise 6.6.2: Show the the ratios given in Table 6.6.2 are dimensionless.

Exercise 6.6.3: Derive eq. (6.6.11)

Exercise 6.6.4: Answer the following questions clearly.

- (a) What is froth flotation? Give three examples.
- (b) Write the names of three industrial flotation cells.
- (c) What is collector? What is its role in flotation?
- (d) Define depressant and activator? Why are they used?
- (e) At what size of the particle does the role of interfacial force become more significant than inertial and gravitational forces? Explain why.
- (f) Explain the conditions under which flotation can occur.
- (g) What is the significance of Zisman plot in flotation?
- (h) Define flotation recovery.
- (i) Define collision angle and critical contact angle.
- (j) What is probability of collision? How would you calculate it?
- (k) Explain the processes involved at the micro-level in flotation.

Suggested reading

Textbooks

- ◆ A. V. Nguyen and H. J. Schulze, *Colloidal Science of Flotation (Surfactant Science Series, vol. 118)*, Marcel Dekker, New York, 2004, Chapter 1.
- ◆ G. J. M. Koper, *An Introduction to Interfacial Engineering*, VSSD, Delft, 2009, Chapter 8.

Reference books

- ◆ L. L. Schramm, *Emulsions, Foams, and Suspensions*, Wiley-VCH, Weinheim, 2005, Chapter 10.

Journal articles

- ◆ R. -H. Yoon, *Int. J. Miner. Process.*, **58**, 129 (2000).