Chapter 5

Particle Removal by Flotation Processes

5.1 INTRODUCTION

Flotation is a process in which suspensions, the particle phase of which has a specific gravity less than that of the suspending medium, are clarified by allowing the suspended material to float to the surface, where it is removed by skimming. In most applications the effective specific gravity of the suspended phase is artificially lowered by the attachment of gas bubbles. This enables the process to be used for a wide variety of suspended solids, the specific gravities of which are slightly greater than those of their suspending media.

The gas bubbles required to effect flotation of solids may be generated in a number of ways, including by electrolytic means, by vacuum-activated release of dissolved gases, by air injection through submerged diffusers and by the dissolution of air at high pressure in part of the flow, with its subsequent release in fine bubble form on reduction of pressure to atmospheric level. The latter method of bubble generation is the preferred method in water industry applications; hence the process as used in water treatment is generally known as the dissolved air flotation (DAF) process.

The process has long been applied in industry (Gaudin, 1957), especially in mining and refineries, for tw0phase separation. It can be used to obvious advantage in water and wastewater treatment systems in place of sedimentation in cases where particle settling velocities are low. Specific uses of the process include:

- to remove paper fibres from pulp and paper mill wastewaters
- to remove oils, greases and similar substances from wastewaters, e.g. food processing, oil refinery and laundry wastes
- to concentrate metallic ores in the mining industry
- to clarify chemically coagulated waters in potable water production
- to thicken sewage sludge

5.2 FLOTATION OF SUSPENSIONS

The analysis of settling velocity of suspensions presented in Chapter 2 is equally valid in the case of suspensions which, because their specific gravity is less than that of the suspending medium, rise rather than settle. The particle settling velocity equations developed in chapter 2 may therefore also be used to obtain the rise velocity of floatable solids, the equation to be used depending on whether the particle movement is free or hindered. Where the buoyancy of a suspension is artificially increased by the attachment of air bubbles, the situation is somewhat more complex since the bubbles increase in size as they rise to the surface.

The solubility of air in water ($c_{s(a)}$, mg l^{-1}) is linearly related to its pressure according to Henry's law:

$$c_{s(a)} = H_a P \qquad (5.1)$$

where H_a is the Henry's law solubility coefficient for air (mg l^{-1} atm^{-1}), which is temperature dependent, and P is the absolute pressure (atm).

The air solubility relationship defined by equation (5.1) also holds good for most industrial effluents, though the value of H may vary from effluent to effluent and in all cases is less than that for clean water. Data on the saturation concentration of air in clean water at atmospheric pressure, in the temperature range 0-50 ^{o}C, is presented in Table 1.6 (Chapter 1) and is also plotted in Fig 5.1.

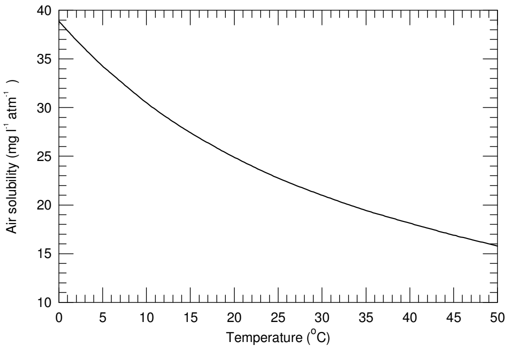

Fig 5.1 **Solubility of air in water at a pressure of 1 atm**

The quantity of air, c_r, which is released from solution per unit volume of pressurized flow when the pressure is dropped from P (atm) to atmospheric pressure, can be obtained from the relation

$$c_r = H_a(KP - 1) \tag{5.2}$$

where K is the fraction of saturation attained at the elevated absolute pressure P (atm). The actual quantity of air released immediately will be somewhat less than the theoretical value since some time is required to reach an equilibrium condition.

5.3 DETERMINATION OF DESIGN AIR-SOLIDS RATIO

The minimum quantity of air required to float a suspension is that which will reduce the effective density (ρ_c) of the resulting air-particle composite below that of the suspending liquid (ρ):

$$\rho_s = \frac{(V_a\rho_a + V_s\rho_s)}{(V_a + V_s)} \tag{5.3}$$

where Va is the volume of air attached to a particle of volume V_s, ρ_a and ρ_s being the respective densities of air and particle. The ratios of the associated air and particle masses are

$$\frac{\text{air}}{\text{solid}} = \frac{a}{s} = \frac{V_a\rho_a}{V_s\rho_s} \tag{5.4}$$

Combining equations (5.3) and (5.4) gives

$$\rho_c = \frac{(1 + a/s)}{(1/\rho_s + 1/\rho_a \cdot a/s)} \tag{5.5}$$

Since the composite particle will rise if $\rho_c < \rho$, the minimum a/s required to effect flotation is obtained by setting $\rho_c = \rho$ in equation (5.5), giving

$$\left(\frac{a}{s}\right)_{\min} = \frac{(1 - \rho/\rho_s)}{(\rho/\rho_a - 1)} \tag{5.6}$$

The air-solids ratio is one of the key parameters in the design of flotation systems.

The required air-solids ratio is best determined experimentally using a flotation cell of the type shown in Fig 5.2. The following procedure may be used:

(1) Partially fill the calibrated cylinder with the suspension to be clarified
(2) Partially fill the pressure chamber with clarified effluent or clean water depending on which will be used in the flotation system.
(3) Release the flow of compressed air through the pressure chamber to saturate its content with air at the desired pressure.
(4) Release a volume of pressurised liquid to provide the desired test air-solids ratio when mixed with the test suspension.
(5) Note the rate of rise of the sludge interface and after a detention time of 20 min measure the suspended solids content of the clarified effluent and the floated sludge.
(6) Repeat for various air-solids ratios.

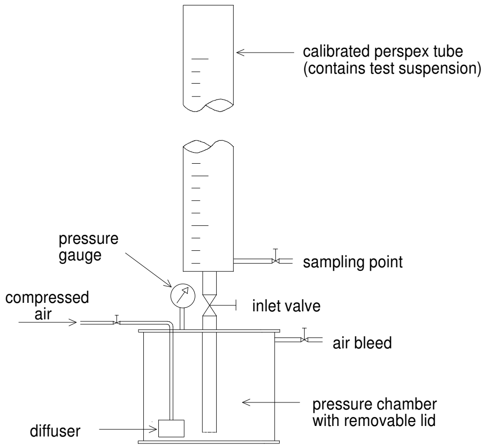

Fig 5.2 **Laboratory flotation cell**

Typical flotation test results are shown in Fig 5.3

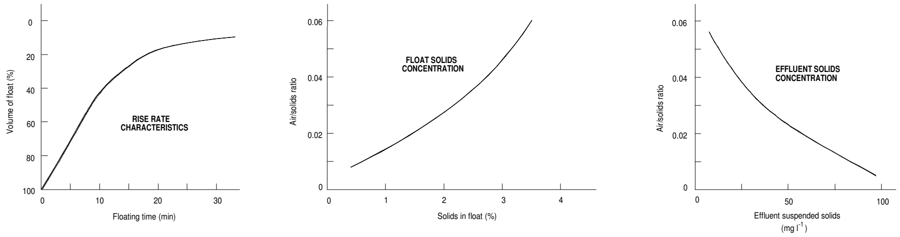

Fig 5.3 **(a)** **(b)** **(c)**

5.4 INTRODUCTION OF AIR

Air may be introduced to the suspension in the form of finely dispersed air bubbles released through a diffuser, or air may be released from solution in the liquid using vacuum or pressure-drop techniques. In vacuum flotation the suspension is saturated with air at atmospheric pressure. The air is released from solution when the suspension is subject to a vacuum in a flotation cell. The vacuum method has the disadvantage that the amount of available air is very limited. In pressure systems part of the clarified effluent, or alternatively a clean water stream, is partly saturated with air at an elevated pressure (4-6 atm gauge). The high-pressure stream is then mixed with the influent suspension at the flotation tank inlet. Under the influence of a reduction in pressure the excess air is released from solution in the form of tiny air bubbles, which tend to nucleate at the surfaces of suspended particles. The pressure method is the one most used in water engineering practice.

Having selected a suitable a/s ratio the required rate of pressurised flow, Q_p, is obtained as follows:

$$Q_p = \frac{(a/s)Qc}{c_r} \tag{5.7}$$

where c is the influent solids concentration. Insertion of the value of c_r from equation (5.2) yields:

$$Q_p = \frac{(a/s)Qc}{H_a(KP-1)} \tag{5.8}$$

5.5 FLOTATION AIDS

Many of the industrial wastewaters amenable to clarification by flotation are colloidal in nature, e.g. oil emulsions, pulp and paper wastes, and food processing wastes. For the best results such wastes must be conditioned by coagulation (Chapter 3) before flotation. In metallurgical flotation processes surfactants are often used to depress the liquid surface tension and create a stable foam, which can retain particles lifted in it.

5.6 DESIGN OF FLOTATION SYSTEMS

The essential elements of a flotation system are an air-saturator and a flotation tank. Schematic layouts are shown in Fig 5.4 (rectangular tank configuration) and Fig 5.5 (circular tank configuration).

Air saturators may be of the packed column type (Casey & Naoum, 1986), as illustrated in Fig 5.4 and 5.5, or may also be of the unpacked column type. The design of these devices is discussed in detail in Chapter 14 (Gas Transfer). They are typically operated in the pressure range 4-6 atm and are designed to achieve up to 90% saturation. The pipe connecting the pressure vessel to the flotation tank is fitted with a special nozzle or throttle valve (Rykaart and Haarhoff, 1994), which effects the required step-change in pressure between the two units. This sudden drop in pressure across the nozzle results in an almost instantaneous release of the now supersaturated dissolved air in the form of very small bubbles, desirable less than 100 µm in size

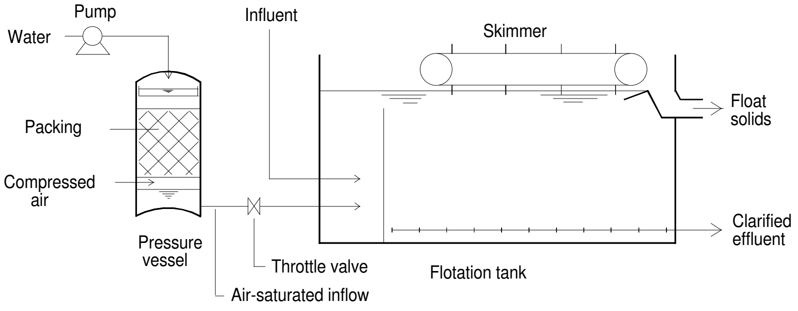

Fig 5.4 Flotation system layout based on rectangular flotation tank

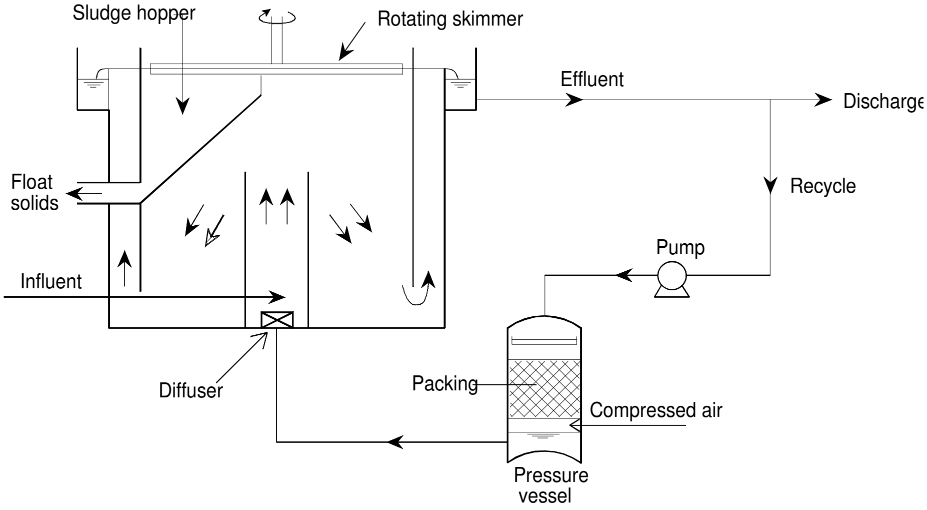

Fig 5.5 Flotation system layout based on circular flotation vessel

Flotation tanks comprise a mixing or reaction zone, in which particles and micro bubble streams are brought together and particle/bubble agglomerates are formed, and a flotation zone. The reaction zone is confined to a separate zone ahead of the flotation zone, as illustrated in Figs 5.4 and 5.5. The flotation zone is designed on the same criteria as sedimentation tanks, i.e. on the basis of rise rate of the suspension and detention time.

The two main applications of the flotation process in water and wastewater engineering are (a) the *clarification* of chemically coagulated waters in drinking water production, particularly for algae-laden waters which are difficult to clarify by sedimentation processes due to the natural buoyancy of the algal biomass, and (b) the *thickening* of activated sludges.

The design ranges that have been used in practical applications (Haarhoff and van Vuuren, 1993) in the clarification of chemically coagulated surface waters and in the thickening of activated sludges are given in Table 5.1. It will be noted that the air quantity required for flotation in water clarification applications is expressed as mg l-1, rather than in a/s ratio terms. Assuming a typical water suspended solids concentration, inclusive of added coagulants, of 20 mg l^{-1} and an air release quantity of 7 mg l^{-1}, the corresponding a/s ratio is calculated to be 0.35. If the specific gravity of the solids is taken as 1.5, the theoretical a/s (min) value is calculated from equation (5.6) to be about 0.0004. Thus, the theoretical value does not provide a realistic guide for design purposes in this area of application.

Table 5.1 DAF design parameter value ranges (Haarhoff and van Vuuren, 1993)

Parameter	Units	Clarification applications	Thickening applications
Reaction zone surface loading	m h^{-1}	40-100	100-200
Reaction zone residence time	min	1-4	0.5-2
Air/solids ratio			0.02-0.04
Air release	mg l^{-1}	6-8	
Cross flow velocity	m h^{-1}	20-100	50-200
Flotation zone surface loading	m h^{-1}	5-11	
Flotation zone solids loading	kg m^{-2} h^{-1}		2-6*, 6-12♣
Flotation zone side wall depth	m	1.5-3.0	2.0-4.0

*without coagulants; ♣with coagulants

5.7 COMPARISON WITH SEDIMENTATION

The flotation process is particularly suited to the clarification of chemically coagulated surface waters that are low in turbidity and have significant algal concentrations (Janssens and Buekens, 1993). Flotation is not suited to very high turbidity waters (>100 NTU). For many water supplies that have a sufficient concentration of natural organic matter that is humic in nature, hydrophobic particles are produced with metal coagulants and there is no need to use polyelectrolytes as coagulant aids (Edzwald, 1994). The hydrophobic nature of the floc particles aids the attachment of air bubbles. The pre-treatment flocculation requirements of flotation are different from those of sedimentation. For flotation, it is desirable to produce small strong floc (particle size 10-30 μm), whereas sedimentation requires large particles that will settle quickly.

The advantages of flotation include:

(1) Floatable and settleable solids can be removed in the same unit
(2) Clarification rates are high, resulting in smaller tank volumes
(3) A more concentrated sludge is produced
(4) Oxygenation effects reduce odour problems
(5) In clarification applications, a smaller floc size is required and hence the use of polyelectrolytes for floc enhancement may not be necessary
(6) Chemical coagulation reactions produce carbon dioxide which is partly stripped out by the DAF process, with the combined benefit of enhanced flotation and improved water stability. This is an aspect of the flotation process that is generally not given due consideration in process design practice.

The disadvantages of note include:

(1) The quality of effluent produced in terms of effluent suspended solids concentration may not be as good as that obtained by gravitational settling.
(2) The process is more costly to operate and maintain than gravitational sedimentation systems.

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Related Reading

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