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WATER CLARIFICATION BY FLOTATION - 1

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A survey of the literature

by

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THE WATER RESEARCH ASSOCIATION

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1. INTRODUCTION

Water purification usually involves solid/liquid separation processes, the most well tried of which are undoubtedly sedimentation and filtration. These are very widely used in the production of potable water and little attention has been devoted to alternatives.

Flotation is a very effective method of solid/liquid separation which has been in use outside the water treatment field for more than half a century. Originally applied in the field of mineral processing, it now provides the means for concentrating over 95% of the world's base metals (1). In addition, it has become increasingly important in such diverse applications as the separation of seeds (2), recovery of wool fat (3), the separation of ink from re-pulped paper stock (4), peas from pea pods (2), coal from slate (5), gluten from starch (6), oils from industrial wastes (7) (8) and more recently in water and waste treatment.

The latter work has indicated that flotation is a possible alternative to sedimentation in water clarification with potential advantages particularly in the treatment of water subject to heavy algal blooms. We believe that the current trend towards increased storage of raw waters known to support algal growth justifies a closer investigation into the potential of this process in the production of potable water. This report is the result of a survey of the literature made as the first step of such an investigation.

Flotation may be defined as the transfer of a suspended phase from the bulk of a dispersion medium to the atmosphere/liquid interface by means of bubble attachment. The three basic processes involved, therefore, are bubble generation, bubble attachment and solids separation. In this report these are described in some detail prior to a discussion of plant design and the application of the process in the water and waste treatment field.

Flotation is a well-developed technology and publications in this field number hundreds per year. Much of this published work relates to mineral separation, the flotation techniques of which are not generally applicable to water treatment. No attempt has been made therefore to survey this in great detail; in any case it has been the subject of numerous books and review articles.

The primary source of reference for this review was Chemical Abstracts which was surveyed back to 1947. Some work prior to this date is referred to which was indicated by later papers. Papers directly concerned with the application of flotation to water and waste treatment were excluded where they lacked sufficient information to be useful.

2. PRINCIPLES OF FLOTATION

2.1. Bubble generation

Although many gases are suitable, air is the cheapest and most readily available for bubble generation. It can be introduced either by dispersion or by releasing air previously dissolved in water under pressure. These two aeration techniques give rise to two basically different flotation systems, termed respectively dispersed-air flotation and dissolved-air flotation. The former finds particular application in the mineral industry, while the latter has been used mainly in sewage and industrial wastes treatment, algae removal, oil removal and water clarification.

Dispersed-air flotation generally involves the use of violent agitation, usually by impellers, to provide dispersion, aeration and agitation of the particle/liquid/air system. The apparatus used is generally termed a flotation cell and when surface-active agents, such as 'collectors' and frothing agents, are employed, the process is known as froth flotation. Alternatively, a gas and liquid stream may be homogenized or air may be diffused through suitable porous media. Dispersed-air flotation systems produce air bubbles of about 1 mm in diameter.

In dissolved-air flotation, the bubbles are generated without the use of violent agitation and Nemerow (9) has referred to this process as quiescent flotation. The bubbles generated are generally much smaller than with dispersed-air flotation and are usually about 0.1 mm or less in diameter.

The solubility of air in water is both temperature and pressure-dependent. Variation of pressure in large air/water systems is more easily controlled than variation of temperature, and dissolved-air flotation techniques are all based on the release of air from solution by pressure reduction.

Air dissolved in the water under atmospheric pressure can be liberated by reducing the surface pressure; this is known as vacuum flotation. Alternatively, air dissolved under a pressure of two atmospheres or more is released by reducing to atmospheric pressure. This latter process, known as pressure flotation, has received greater acceptance than vacuum flotation due to the larger pressure drop available and a significant advantage in terms of capital cost (5). Vacuum flotation has, however, been of valuable service for many years in the pulp and paper industry for recovery and concentration of fibres (10).

Recently, studies have been made of the use of electrolysis as a means of bubble generation, giving rise to the process known as electrolytic flotation (11)(12)(13). This method has undergone successful trials in a pilot-scale waste reclamation plant (12) and has been used for thickening sewage sludge (14).

2.2. Bubble attachment

Vrablik (5) has defined three methods of bubble attachment which can lead to flotation.

(i) Adhesion of a gas bubble to the suspended phase as a result of either:
  (a) collisions between the bubbles and the suspended phase, or
  (b) precipitation of the bubbles onto the suspended phase, a process of nucleation.

(ii) The trapping of rising gas bubbles in a floc structure.

(iii) The absorption of gas bubbles into a floc structure as it is formed.

Although in dissolved-air flotation, bubble attachment can proceed by all of these methods, in dispersed-air flotation method (iii) does not apply as the bubbles are large and rise too rapidly to allow their incorporation into a growing floc structure. In dissolved-air flotation the slow rise of much smaller bubbles can permit absorption in the floc structure.

The significance of method (i)(b) in dispersed-air flotation is the subject of some controversy. It has been claimed that in mineral separation, regions of high and low pressure before and after the impeller blades produce supersaturation and undersaturation respectively. This could lead to the precipitation of air directly onto the surface of the mineral particles. Direct photographic evidence has shown however that the collision mechanism is predominant in dispersed-air flotation (15)(16)(17).

To ensure that a collision is followed by bubble/particle adhesion it is almost invariably necessary to add surface-active agents in dispersed-air flotation. With dissolved-air flotation, where the bubbles are relatively much smaller, the adhesion caused by collision is only one of several concurrent mechanisms, which, it appears (10), do not necessarily demand the use of surface-active agents.

Many phase separations by flotation involve a suspended phase, the surface of which is initially intimately associated with its water environment, i.e., there is no precise boundary region or interface. When such a strong affinity exists between the water and the suspended phase, the particles of the suspension are termed hydrophilic, and bubble adhesion cannot occur, as the air cannot displace water from the surface of the particle.

It is essential in dispersed-air flotation to reverse this effect by reducing the affinity between the water and the particles, that is, making them hydrophobic. This is achieved by adding surface-active agents, which are usually linear hydrocarbons with a polar or chemically active group at one end of the molecule. Sites exist on the surface of the particles which are receptive to these polar groups and adsorption of the molecules can occur. Once attachment is established, the hydrocarbon 'tails' of the molecules, which have little affinity for water, can penetrate the air/water interface of adjacent bubbles. Bridging thus occurs between the suspended particles and the bubbles, the forces involved being sufficiently strong to permit particle flotation.

Generally, the more hydrophobic the surface, the greater the bubble adhesion and the better the flotation. An assessment of hydrophobicity is therefore of importance in dispersed-air flotation and this can be achieved by measurement of the contact angle. This is the angle between the plane surface of a solid particle and an air bubble in water (Fig. 1).

At equilibrium the interfacial tensions at a point of three-phase contact must balance, thus

$$T_{AS} = T_{WS} + T_{AW}\operatorname{Cos}\theta$$

or

$$\operatorname{Cos}\theta = \frac{T_{AS} - T_{WS}}{T_{AW}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots 1.$$

where T_{AS}, T_{WS} and T_{AW} are the air/solid, water/solid and air/water interfacial tensions, and θ is the contact angle measured through the water.

A contact angle of zero means that the surface is hydrophilic and water covers the solid in preference to air so that air-to-solid contact becomes impossible. A contact angle of 180° would mean that air covered the solid preferentially, indicating a high degree of hydrophobicity; in fact, the highest contact angle recorded is about 110° (17). The larger the angle of contact, the more hydrophobic is the surface of the solid. The aim in dispersed-air flotation is to make the surface of the particles sufficiently hydrophobic to ensure efficient bubble-particle adhesion. The corresponding value of the contact angle can vary considerably in different systems e.g. the maximum contact angle for dimethyl dithiocarbamate coated galena is 50° and for n-heptyl xanthate coated galena 90° (15).

The surface-active agents used for this purpose in mineral flotation are generally termed collectors. Their performance can be modified by the addition of other chemicals (18), including frothing agents, and regulating agents or modifiers. The latter include flocculants and a variety of reagents (activators, depressants and dispersants) whose function is to promote preferential adsorption of the surface-active agents on a chosen mineral species enabling selective flotation to take place. This technique of mineral separation is a highly developed science and there are a number of books and good reviews of the subject (1)(2)(15)(16)(18).

In dissolved-air flotation, where mechanisms in addition to adhesion apply, the measurement of contact angle serves little useful purpose. Although these mechanisms permit flotation of hydrophilic particles, it is however reasonable to assume that the presence of surface-active agents could have a beneficial effect by increasing the contribution made by the adhesion mechanisms. Virtually all submerged surfaces have attached to them very small gas bubbles, generated chemically or formed by slow precipitation from solution (15). These could be important in dissolved-air flotation by acting as sites for nucleation of air precipitating from solution.

If the suspended phase is not naturally flocculant, electrolytes (7)(8)(19)(20)(21)(22); polyelectrolytes (19)(22)(23); activated silica (7)(8); glues (22) or other suitable flocculants may be used to improve flotation by producing a floc with suitable characteristics. Floc formation can occur before, during or after the precipitation of the gas phase, but as it is desirable to avoid the breakdown of any preformed floc (3)(5)(24)(25) it is preferable either to develop the floc during or after pressure release (21) or to pressurize a portion of the effluent only and recycle this with the influent (3)(7)(8)(23)(25) (26)(27). This latter method has other advantages which will be discussed later.

2. 3. Solids separation

The efficiency of dispersed-air flotation is dependent on the size of the particles present, the surface-active agents used and the quality of air used. There is a great deal of evidence in mineral flotation studies to suggest that there is an optimum particle size for flotation, in that flotation efficiency decreases if the particle size is either increased or decreased from this value (1)(17). With pyrites, for example, a maximum flotation rate was found at a particle size of about 60 μm (16).

The difficulty with very fine particles (e. g. less than 10 μm) is due at least in part to the fact that the mass of the particle may be insufficient to permit it to rupture the liquid film between it and the bubble in the available time of contact (1). Thus colloidal, particles, whose approximate size limits lie between 1 nm and 1 μm are difficult to remove by flotation, unless a flocculating agent is employed. Fleming (1) recognized the problem of particle size in mineral flotation and suggested that for fine particles, bubble precipitation methods had advantages over techniques depending on direct collision for bubble-particle adhesion.

With increase in particle size beyond the optimum a critical point is reached beyond which flotation rapidly deteriorates as the mass of the particle overloads the carrying capacity of the bubbles. It has been shown (15) that the forces binding a bubble and particle together depend upon the surface tension and the contact angle. The force tending to part them, under stationary conditions, is the sum of the weight of the particle and the buoyancy of the bubble. During upward movement an accelerating force is exerted upon the particle for such time as it takes the particle to acquire the same velocity as the bubble. Although this is relatively unimportant for small particles, it is of considerable importance for larger particles. When rising under steady conditions, the force tending to part bubble from particle is the viscous drag provided by the water on the particle. If this drag exceeds the adhesional force then the bubble and the particle will become separated. The drag increases with increase in particle diameter at a faster rate than the adhesional force.

In mineral flotation it is invariably found that the greater the number of bubbles of a given size per unit volume, i.e. the greater the aeration intensity, the faster is the rate of flotation (15). In the foam separation of micro-organisms however, an optimum aeration intensity is generally indicated. Rubin and Cassell (28), investigating the microflotation of bacteria, found that redispersion of the surface layers into the bulk of the solution occurred at high aeration rates while good separation was achieved at low rates. Grieves and Schwartz (29), working with a continuous foam flotation system for water clarification, concluded that as low an air flow-rate as possible should be used in the process. Levin and Barnes (30) also found that the most economical harvesting of algae by froth flotation occurred at low aeration rates employed for relatively short aeration periods.

In dissolved-air flotation, to obtain satisfactory removal of the suspended particles and concentration of the surface sludge after pressure release, the optimum retention time of the air/water mixture in the flotation unit must be determined. The time required for flocculation is usually about 10 to 15 minutes, and it has generally been found that total retention times between 10 to 40 minutes are necessary (7)(10)(31), an average retention time of 20 minutes being most frequently used (3)(21)(25). Eckenfelder et al (25) found that in the case of sewage sludges, retention periods greater than 20 minutes effected no substantial change in effluent quality or sludge concentration. However, Gardner (32) has stated that for systems where thickening is the main requirement, retention periods greater than 30 minutes are necessary in the flotation tank.

The effect of temperature fluctuation on dissolved-air flotation has generally been neglected. As the solubility of air decreases with increasing temperature (in distilled water it is reduced by 45% on increasing the temperature from zero to 30 °C) (5), a large temperature fluctuation may have a significant effect on flotation efficiency. Water temperature is also important because of changes in fluid viscosity. Theoretically (33), approximately 20% more air may be dissolved at $276 kN/m^2$ in a temperature change from 20 to 10 °C; however, this is also accompanied by a 30% increase in dynamic fluid viscosity, which produces the potential net effect of lower process efficiency.

3. PLANT DESIGN

3.1. General characteristics

The following characteristics are common to all flotation separators:

(a) a solids/liquid separation vessel, or tank fitted with an inlet and an outlet for the liquid stream.

(b) a facility for introducing gas bubbles,

(c) a facility for removing the floated scum.

Figs. 2 to 6 illustrate five types of flotation separators based on dispersed air, dissolved air and electrolytic bubble generation techniques.

Fig. 2 shows a typical dispersed-air flotation cell as used in the mineral processing industry. Bubbles are introduced by the action of an impeller, which sucks air down a central tube into the bulk of the liquid. Particle/bubble contact occurs, floating the mineral to the surface where it is collected in a scum trough.

A foam flotation column, similar to the type used by Grieves, is shown in Fig. 3. In this, a stream of bubbles is introduced into the column by the dispersion of air through a sintered glass aerator. The foam is collected in a similar manner to that of the mineral flotation cell.

In Fig. 4 a rectangular dissolved-air flotation unit is shown, where water saturated with air under pressure is introduced into the raw water stream. In the flotation unit the bubbles formed by precipitation from solution float the suspended matter to the surface, forming a scum which is removed by a skimmer.

A circular flotation unit suitable for dispersed-air or dissolved-air flotation is shown in Fig. 5. In this, the bubbles are introduced with the raw water, which flows down a central tube and then up a second concentric tube where solid/liquid separation occurs. The bubbles remove the suspended material to the water surface, forming a scum which is again removed by a skimmer. The clarified water then flows down a third concentric cylinder to the water outlet.

Finally, Fig. 6 shows an electrolytic flotation unit, similar to a dissolved-air flotation unit, except that the bubbles are generated by electrolysis.

3.2. Factors in plant design

The development of equipment for dispersed-air flotation has proceeded almost entirely along empirical lines. Arbiter and Harris (16) in 1961 reviewed the development of flotation machines in the United States, the factors affecting machine performance and the theoretical background to flotation. They concluded that the development of rational design procedures for flotation equipment will await elucidation of the predominant flotation mechanisms.

Glembotskii, Klassen and Plaksin (34) have given an account of flotation machine development in the USSR together with the general principles governing the operation of these machines. Development has concentrated on mechanical flotation cells using impellers for air dispersal and, with these, the main effort has been to find the most suitable impeller design. These authors showed that the parameters most affecting the design and selection of a flotation machine are linked with the properties and composition of the material to be concentrated and are dependent on the reagent feeds used. For example, if large particles are to be floated the cell must be shallow, giving a high rate of pulp mixing in the lower part and being free from turbulence in the upper part. Where fine slimes have to be floated a lower rate of pulp mixing is permissible, but the pulp must be aerated with extremely small bubbles and by the evolution of gases from solution; the cell can therefore be relatively deep.

In dissolved-air flotation, Masterson and Pratt (31) have given an account of the application of pressure flotation principles to process equipment design, in which they describe the main characteristics of some essential flotation unit components. These include a pressurizing pump which maintains the inflow to the unit at an elevated pressure of between 172 and 414 kN/m^2 (25 and 60 lb/in^2). Air, which is entrained with the water on the suction side of the pump, is thus forced into solution by the increased pressure in a retention tank or air/liquid contact vessel linked to the pressurizing pump. This vessel allows 30 to 60 second contact between the air and water for effective air dissolution.

A back-pressure regulating device is generally employed to maintain as nearly constant a discharge head as possible on the pressurizing pump. This is usually a valve of design such that clogging by suspended material in the water does not occur. From this valve the pressurized water flows into the flotation tank which is usually rectangular or circular in design. The inlet to this tank is generally located and directed to dissipate the pressurized water as uniformly as possible. In circular tanks this is achieved by a spiralling or radial flow inlet and in rectangular tanks it is usual to place the inlet opposite to the outlet, as with horizontal flow sedimentation tanks, but with an adjacent baffle to direct the flow upward. The point of air release is generally located remote from the area where the floated material is to be skimmed from the surface to prevent escaping free air interfering with the process.

If the inflow contained sand, grit or other dense materials which would not respond to flotation, allowance would have to be made for their removal. Similarly if the raw water required chemical treatment, dosing facilities would have to be accommodated in the design of the system. Dosing would generally be effected immediately before or after the pressurizing pump.

D'Arcy (35) has listed the following as important design considerations in dissolved-air flotation.

(i) Dissolving the maximum amount of air in the influent.
(ii) Elimination of all entrained air, as the release of entrained air in the flotation chamber introduces turbulence.
(iii) Proper hydrodynamic design of the entire flotation system, especially the flotation chamber.
(iv) Continuous mechanical removal of the floated surface scum.
(v) Design of the entire system to produce a unit which will operate automatically under a wide range of conditions and which requires a minimum number of trained personnel for its operation.

Baum and Hurst (24), in an analysis of flotation applied to municipal and industrial waste treatment, stated that both circular and rectangular flotation units were suitable for dissolved-air flotation. However, with equal conditions before the units, a rectangular form where the length was between twice and three times the width and a constant depth of 12 to 18 m gave better results when the flows were in excess of 0.302 litre/sec and below 12.1 litre/sec.

They also showed that the presence of unattached or free air bubbles could cause turbulence and disturb the separation, requiring a longer retention time to allow the rising solids to surface. Furthermore, when chemical flocculation was employed they found it preferable to form a floc rapidly very slightly in advance of the gas precipitation, thus a nucleus was present for bubble formation and the growing floc was not disturbed by excess hydraulic shear as it had already entered the flotation chamber.

Generally there is a lack of authoritative information given concerning the loading of flotation units, i.e. the flow for a given size. Jones (36), for example, has claimed that the maximum hydraulic loading or overflow rate is 0.55 mm/sec and Mayo (27) stated that the inflow to the unit should not exceed 1.35 mm/sec. D'Arcy (37) suggested a value of 1.63 to 4.89 mm/sec while Masterson and Pratt (31) recommend overflow rates of 0.816 to 3.26 mm/sec. More recently, Lundgren (38) has stated that under general conditions loading rates are designed on the basis of about 1.7 mm/sec. Reporting units capable of handling 0.21 m^3/sec, he showed that with improved design, loadings of up to 3.4 to 5.4 mm/sec would be possible. It is probable that these discrepancies arise from the differing characteristics of the waters being treated or perhaps from the differing hydraulic conditions resulting from the design of the flotation systems used. However, it is recognized that as a separation process for the removal of suspended material from water, flotation is faster than sedimentation (Sect. 5).

Various rising velocities have been quoted for floc systems during flotation. Activated sludge derived from domestic sewage was found to have an initial vertical rise rate varying from 0.85 to 2.1 mm/sec to 4.23 mm/sec (25). Alum sludge from water treatment plant (39) was found to have rise rates varying from 20 mm/sec to 35 mm/sec depending on the chemical conditioning of the sludge employed. These rising velocities are far greater than settling velocities for aluminium or iron floc encountered in water treatment works, where a settling velocity of 0.5 mm/sec would be considered better than average. Katz (40) has considered the rate of separation of suspended matter in the flotation process from the viewpoint of the Stokes' equation governing the motion of a sphere through a viscous medium. This may be expressed as:

$$Vo = \frac{2a^2 g\,(\sigma - \rho)}{9\eta} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots 2.$$

where Vo = the terminal velocity of the sphere (the eventual steady velocity)

a = the radius of the sphere

g = the acceleration due to gravity

σ = the density of the sphere

ρ = the density of the liquid

η = the viscosity of the liquid

According to this equation the rate of separation is directly proportional to the difference in the densities of the liquid and the suspended particle, and is inversely proportional to the liquid viscosity. However the factor which most strongly influences the separation rate is the radius, or size, of the particle because the terminal velocity is proportional to the square of the radius. Thus if it is possible to double the radius or size of the suspended matter, a fourfold increase in separation rate may be possible.

Katz conducted laboratory experiments on bentonite/aluminium sulphate systems to establish a relationship between the rate of use and the particle size. Photographic evidence showed that as the average particle size was doubled, the rate of rise also doubled. As these results do not comply with Stokes' Law, Katz attributed the reduced effect of increasing the particle size to hindered separation, but made no attempt to explain the phenomena. The inconsistency of the results obtained by Katz and those predicted by Stokes' equation may be attributed to the dissimilarity between solid spheres and floc particles.

Howe (41) has given a mathematical interpretation of flotation for solid/liquid separation limited to the flotation of discrete particles without the interference of surface active foaming agents. He has stated that previously flotation techniques have developed on an empirical basis, although there are theories which explain the phenomena of flotation. His derivation started from a differential equation of motion which was expanded to give solutions for the rising velocity of a particle with changes in the applied rising force, particle diameter, liquid viscosity and particle density. The following equation was then evolved which allowed the ratio of solids removal, R, to be evaluated:

$$R = 1 - e^{-\left(\frac{Vr}{Q/Ah}\right)} \qquad \ldots\ldots\ldots\ldots\ldots\ldots 3.$$

in which R, the ratio of total removal of solids after flotation, equals $1 - \frac{Co}{Ci}$,

where Co = the effluent suspended solids
Ci = the influent suspended solids
Vr = the rising velocity of a single particle/air bubble
Q = the flow applied to the flotation unit
Ah = the horizontal area of the unit.

This ratio was shown to be governed by the effective depth of the tank, the overflow rate and the time provided for the particles to reach the surface of the liquid from the bottom of the tank. For an efficient flotation tank to be designed, the possible maximum removal of solids must be determined, which, according to Howe, could only be obtained from data after carefully planned experiments interpreted by his derived equations. The practical applications of his mathematical derivations are apparently not limited to dissolved-air flotation, and Howe concluded by saying that he expected that his mathematical explanation would be an introduction for further research.

Mayo (27) has listed the following design parameters as necessary requirements for consistent efficiency in flotation operations:

(i) An air-to-solids ratio of 0.02 (agreeing with the findings of Eckenfelder et al, see below)

(ii) Particle agglomeration - fine particles must be coagulated

(iii) Hydraulic loadings - the inflow to the unit should not exceed 1.35 mm/sec.

Jones (36) in an extensive discussion on the sizing and application of dissolved-air flotation thickeners has given some of the developments in the design and sizing of flotation units which have led to current design criteria. He indicated that a high degree of saturation of air would be required in the recycle at an operating pressure of about 413 to 482 kN/m^2, (60 to 70 $lb/in.^2$) that a solids loading for a given recycle rate rather than a recycle ratio (recycle flow/effluent flow) would be significant and that provision should be made for auxiliary recycle and the use of flotation aids.

Eckenfelder et al (25) stated that in the evaluation of flotation variables for process design, it would be convenient to employ a dimensionless air-to-solids ratio. This ratio they defined as the weight of air released divided by the weight of suspended solids treated. An air-to-solids ratio giving the most favourable process performance in the laboratory could then be used for plant design, provided the plant and laboratory operating conditions were approximately equivalent. With, for example, activated sludge the most favourable process performance was obtained at an air-to-solids ratio of 0.02.

Ettelt (42) investigating activated sludge thickening by dissolved-air flotation, found that the performance of the flotation unit was greatly dependent upon two factors:

(i) proper inlet design to provide the maximum bubble adhesion efficiency by reducing turbulence and increasing the intimancy of the air bubbles and solids, and

(ii) finding the optimum use of recycle to increase the maximum rising velocity without decreasing the production of floated solids.

He further found that, contrary to some reports, the effluent solids content was not dependent on the air-to-solids ratio except for very low air input rates or high solids loading rates. Ettelt appears to have ignored Howe's earlier mathematical treatment in this investigation, as he states that the mathematical relationships in the literature of the particle mechanics in flotation are deficient simply because they cannot be readily applied to flotation operations.

Mulbarger and Huffman (33) have recently reported an investigation into mixed liquor solids separation by flotation. In this they concluded that conventional design criteria such as solids loading rate and air-to-solids ratio, did not fully characterise flotation performance and offered a new parameter, developed from Howe's theoretical relationship, as a more rational design and operational guide line. They used his equation as a theoretical justification for the separation of discrete, homogeneous particles by flotation and attempted to describe it in terms of meaningful design variables. Their mathematical model, which considered hydraulic conditions and predicted effluent quality, could be expressed graphically and could show when a flotation process was stable, unstable or when it would fail. This relationship would particularly apply when effluent quality was a major design consideration. Their work should be of benefit to others investigating dissolved-air flotation systems.

Rohlich (7) has given the results of extensive pilot plant studies of oil removal from refinery waste by dissolved-air flotation. This work emphasized the advantages of introducing the air by recycling a proportion of the treated water. Investigating three different methods of handling the flow: entire influent, partial influent and partial effluent pressurization, (Fig. 7) it was found that for comparable amounts of air supplied, the most efficient oil removal was effected with partial effluent pressurization. Rohlich also described a portable flotation kit for on-site testing of various industrial wastes and sewages to determine the effectiveness of the flotation process for each system.

It is apparent that in early designs of flotation units, either the entire inflow or part of the inflow was pressurized; this however produced clogging problems and difficulty with varying flows. It is claimed (36) that F. S. Gibbs introduced effluent pressurization during the 1940's to overcome these problems. Other workers have also referred to the importance of effluent pressurization. Vrablik (5) has pointed out that greater amounts of gas must be dissolved and consequently greater aeration pressure would be required by this method if the same air-to-solids ratio as that obtained with total pressurization was to be maintained. Mayo (27) found that effluent pressurization gave the best results, and Geinopolous and Katz (26) have shown that effluent pressurization has advantages over total pressurization as it avoids floc break-up and equipment and power costs are lower since considerably less liquid must be pressurized. Eckenfelder et al (25) came to similar conclusions when considering flotation of biological sludges, stating that pressurization of the clarified effluent resulted in superior effluent quality and economy in power. This is particularly true for flocculant sludges which are dispersed by high shearing stresses. They found it was necessary to evaluate empirically the required effluent recycle to be pressurized for each specific application.

Recycle rates suggested by various workers have varied between 10 and 100% of the raw water flow, 25 to 50% being common for sewage and industrial waste treatment. Gardner (32) suggested that for saturation pressures of between 276 and 415 kN/m^2 (40 and 60 $lb/in.^2$) the required recycle of clarified effluent would generally be up to 50% of the inflow. The volume of air necessary for injection into this recycle stream was equivalent to 5% of the inlet flow at the stated saturation pressure. He stated that up to 50% of saturation could be achieved using conventional designs of pressure vessel, but with mechanical mixing or packing this could be increased to 90%.

It has been stated (15) that probably all submerged surfaces have very small gas bubbles attached to them, formed by slow precipitation or chemical means. If the solution and solid are subjected to a high hydrostatic pressure, as in total influent pressurization, these gas bubbles are forced into solution. Thereafter, despite high supersaturation, bubbles form with the greatest of difficulty. In view of this, it might well be expected that effluent pressurization would give superior results to total pressurization where, presumably, a proportion of the intrinsic bubbles have been lost during pressurization. With effluent pressurization these bubbles would be unaffected and could provide sites for the nucleation of precipitating air bubbles.

4. THE APPLICATION OF FLOTATION TO WATER AND WASTE TREATMENT

4.1. Sewage and industrial wastes

The increasing importance of flotation for the removal of suspended particles in sewage and industrial wastes may be reflected by the expanding literature on this subject and the growing number of companies manufacturing flotation units. The development of such units has largely resulted from research work in the United States and Sweden.

Early work was based on variations of dispersed-air flotation. Hansen and Gotaas (43) successfully applied foam flotation columns in studies on sewage, paper mill and textile wastes employing a heteropolar laurylamine hydrochloride as the flotation reagent. The high cost of this reagent, however, resulted in the conclusion that the process was economically unsuitable for sewage. Newe, Schmidt and Szniolis (44) reported studies on the flotation of sewage using 28 different detergents, and emphasized the importance of developing a low cost flotation reagent.

The vacuum generation of gas bubbles for mineral flotation was conceived by Elmore (B. P. No. 17 316:1904), and vacuum flotation was later developed by the Scandinavian paper industry (45)(46) for recovering valuable paper-making materials. These units, commonly termed flotation Save-Alls or Sveens (after the Sveen-Pedersen process), have been extensively employed since World War 1 for paper-mill 'white-water' clarification, evolving into the dissolved-air flotation systems that are used today (22). Vacuum flotation has also been used successfully to remove grease and suspended solids in the treatment of sewage and industrial wastes (47)(48)(49).

D'Arcy (37) and Ashley (50) have discussed the use of a dissolved-air flotation system giving good results in the treatment of industrial wastes. Air was introduced into the influent, usually at the suction side of a centrifugal pump and dissolved under 172 to 276 kN/m^2 (25 to 40 $lb/in.^2$) pressure in a detention tank. On pressure release the dissolved air was precipitated from solution at the inlet to a flotation chamber. The air bubbles produced carried the suspended particles to the surface, gradually forming a concentrated sludge which was removed by mechanical scrapers. The clarified water was withdrawn from the bottom of the chamber, clarification being enhanced by the addition of suitable flocculating agents.

Barry (8) has described a flotation unit in which air was introduced into a portion of the effluent by means of a diffusion assembly placed at the inlet of a recirculating pump. Part of this aerated recirculated effluent was then mixed with the influent of the system, the remainder being introduced at the bottom of the tank to effect additional flotation.

Brown and Thomas (23) reporting results obtained utilizing effluent pressurization in the consolidation of surplus activated sludge, found that the use of polyelectrolytes in preconditioning increased the removal rate and helped clarification. The sludge could be thickened to up to 5. 0% solids by the process. It is also interesting to note that the authors considered that flotation encourages flocculation of the suspended sludge particles. Braithwaite (51) had previously shown the benefit to be gained by use of polyelectrolytes during a series of tests on the flotation of activated sludge. With the application of polymers, he found it possible to increase the solids yield by a factor of 3. 7.

Hilmer (19), in a paper on the subject of chemical precipitation, flocculation and flotation, has described dissolved-air flotation plant and has given results for various sewage treatment plants in Sweden and the USA. It is evident from his figures that large reductions in suspended solids, BOD and phosphate are possible. For example, flotation with alum treatment employed on an experimental basis at a sewage treatment plant at Detuxent, USA, has reduced the average suspended solids from 300 to 20 mg/litre, the BOD from 140 to 7 mg O_2/litre and the phosphate from 2400 to 100 mg/litre.

Following their successful work on algal flotation in South Africa (Sect. 4. 2) van Vuuren et al (21) have investigated a system for the purification of sewage works effluent by means of lime softening and flotation. This system involved the use of excess lime as coagulant in the flotation unit and, although aluminium sulphate was found to be equally effective as a flotation flocculant, the use of lime softening was preferred for its sterilizing action, complete removal of phosphates and decrease in mineral content. In the design of the flotation unit provision was made for continuous removal of scum build-up by the use of a surface skimmer, any settleable material being removed by means of a conical bottom draw-off (Fig. 5). It was found to be essential that moderate aeration under flash mixing conditions should be applied as the fine scum layer tended to break up under prolonged turbulent conditions. Micro-bubble aeration was necessary for entrainment and buoyancy of the floc, and was achieved by introduction of air prior to a centrifugal pump. This proved to be the most effective, simple and economic system in comparison with conventional pressure aeration systems. The adverse effect of air coalescence on flotation efficiency was also completely eliminated by maintaining a critical minimum velocity in the feed-line after introduction of the air. The object was to have finely dispersed air bubbles present before the flotation flocculant was added, in order to effect air entrainment in the growing floc. This aspect was found to be of fundamental importance in the efficiency of flotation.

In a later paper van Vuuren et al (52) described a laboratory scale flotator developed for the stripping of organic pollutants from various effluents of sewage works, fish factories, pulp and paper mills and abattoirs. The unit contained a dispersed-air generating system which introduced air on the suction side of a pump, thus avoiding the use of high pressure flotation equipment. This system was found to be useful for on-site investigations concerning flocculation/flotation of various organically-polluted effluents.

Ettelt (42) has reported that dispersed-air flotation studies on activated sludge gave a maximum solids concentration of only 2. 8% compared with the 2% obtainable by settling. He considered that this gain was not significant and therefore gave his attention to dissolved-air flotation. Using this technique he was able to thicken the sludge to 4% solids.

An extensive report on the use of dissolved-air flotation treatment of combined sewer overflows (39) showed that a dissolved-air flotation process requiring twelve minutes' retention time removed suspended solids from combined sewage as effectively as conventional clarifiers requiring four hours' retention time. During periods of rain and in the absence of chemical aids, the process removed 69% of the suspended solids remaining after the separation of large particles by screening. Addition of aluminium sulphate and polyelectrolyte increased the removal of suspended solids to an average of 84% . Aluminium sulphate alone was ineffective. The BOD reduction without chemical aids averaged 26% but increased to 42% on coagulant addition. After drying, the solids content of the floated sludge was between 5 and 7% which suggested that the sludge thickening step normally employed could be dispensed with. It was found essential to provide cover against wind and rain to obtain full efficiency of the flotation tank.

Gardner, discussing flotation techniques applied to the treatment of effluents (32), considered dissolved-air flotation to be suitable for most separations where the density of the suspended particles is similar to that of water. However he claimed that the process was somewhat concentration dependent as in practice up to 95% of suspended matter could be removed at initial concentrations of 150 to 220 mg/litre but at lower initial concentrations the percentage removal fell. A treated water suspended solids content of 10 mg/litre or less was nevertheless obtainable.

Investigations on flotation treatment of sewer overflows (39), showed that a flotation tank 3.7 m long by 3 m wide could treat 0.025 m^3/sec. Two such tanks with additional ancillary facilities would require 32.5 m^2 of land area compared with 335 m^2 necessary for a 0.05 m^3/sec conventional clarifier. It was found possible to maintain a 60% reduction in suspended solids treating 0.05 m^3/sec in a flotation tank 3.7 m long by 3 m wide with a liquid depth of 0.49 m. This is equivalent to an overflow rate of 4.5 mm/sec.

Raw sewage sludge thickening by flotation using a heating process has been reported (53), which involved heating the sludge to 35 °C, thereby effecting flotation and consolidation of the suspended material. Addition of a polymeric flocculating agent was found to improve the thickening process considerably.

Production of gas bubbles by electrolysis of water was suggested by Elmore (British Patent 13 578:1904) but it has only recently been adopted as an industrial flotation technique. One such electrolytic thickening process for industrial water re-use (12), comprised a shallow rectangular tank provided with a pair of horizontal electrodes situated near the tank bottom. The upper electrode, the anode, was in the form of a grid, whilst the cathode was usually in the form of a solid sheet. The waste water was fed between the electrodes which were connected to a low voltage supply. A two-fold effect was then said to follow; the charge on the electrodes neutralized that carried by the suspended particles so they were able to flocculate, and electrolysis of the water generated gas bubbles permitting floc flotation (12). The application of this technique to oils and grease removal (12) and to the treatment of paint keg wash liquors containing finely divided solids (54) has been reported.

One of the main factors in the development of electro-flotation processes is the design of the electrodes and their materials of construction (B). Various designs have been used including a single combined electrode, bars, perforated plates and wire mesh, whilst materials have ranged from normal mild steel through titanium and platinum. It was considered that if the problems associated with electrode material and its frequency of replacement could be resolved, electro-flotation would play an increasingly important part in the treatment of industrial effluents and sewage.

Hillis (55) in a review of electrolytic treatment of effluents has referred to the work of Føyn in Norway and Axell in New Zealand. In Norway, electrolyzed sea water was used to treat sewage in order to reduce the nitrate and phosphate content of the effluent. Sewage and sea water were mixed and passed through an electrolytic cell and the magnesium ammonium phosphate which formed was precipitated in the alkaline environment of the cathode. Hydrogen evolving at the cathode then floated the magnesium ammonium phosphate floc and suspended solids to the surface where they were removed by a scraper. The hypochlorite solution produced at the anode was mixed with the final effluent and effected sterilization. A pilot plant has been successfully used to treat the sewage from a population of 1 200. In New Zealand, Axell employed electrolytic flotation for the treatment of sewage and was able to remove 73% of the suspended solids and 56% of the BOD with a power consumption of 1 kWh/m^3 treated water.

4.2. Bacteria and algae

The separation and concentration of bacterial spores and vegetative cells by means of froth flotation has been reported by Boyles and Lincoln (56), who made studies on a variety of cultures employing various air flow-rates. Leven and Barnes (57), investigating froth flotation for harvesting algae, concluded that the process approached an economically acceptable level and that it may have use as a sewage treatment process. Rubin and Cassell (28) investigated the effectiveness of microflotation which they defined as a low gas flow-rate foam separation technique for the removal of dispersed microscopic substances such as bacteria and algae. They achieved high rates of bacteria removal at low gas flow rates using lauric acid as 'collector', absolute alcohol as frother and aluminium sulphate as a flotation aid. Further work utilizing froth flotation for harvesting algae and other micro-organisms has been reported by Smith, Funk and Proctor (58), and Dobias and Vinter (59).

It has been pointed out by Golueke and Oswald (60), after comparing various methods for algal processing, that the major disadvantage in froth flotation of algae is the need for a substantial pH adjustment in the liquid medium in order to obtain optimum flotation conditions. Cassell et al (61), investigating the removal of organic colloids by micro-flotation, concluded that the process could in many water treatment systems replace coagulation-sedimentation with considerable saving in space. Coupled with high rate filters, they proposed that microflotation could lead to a complete water treatment process that would be compact and well adapted to emergency portable units as well as large installations.

Funk, Sweeney and Proctor (62) used dissolved-air flotation for harvesting Chlorella algae with ferric sulphate as coagulant. Employing air saturation pressures of 103, 206 and 310 kN/m^2 (15, 30 and 45 $lb/in.^2$) they found that the maximum time taken for harvesting was 10 minutes at high pH values (9.0 and 10.0) and less than 1 minute at low pH values (3.0). This compared well with the shortest satisfactory sedimentation time which they found was approximately 30 minutes.

Van Vuuren et al (20) have developed a simple and economic technique for the continuous removal of planktonic algae from water. In earlier work (63) a combined sedimentation flotation unit had been evolved which showed that partial flotation occurred as a result of the entrainment of minute gas bubbles by the algal floc. This directed attempts to improve algae flotation, resulting in a continuous system dependent upon high dissolved oxygen concentrations originating in water through the photo-synthetic activity of the algae. During periods of low dissolved-oxygen concentrations flotation could be maintained by pre-aeration under pressurized conditions. It was found that rapid algae flocculation using aluminium sulphate was a pre-requisite for efficient flotation and it was suggested that polymeric flocculant aids could improve planktonic flotation. The required retention time in the flotation tank was only 12 to 15 minutes, and provision could be made in the tank design for the removal of any settleable material. Using 400 mg/litre aluminium sulphate as flocculant, it was possible to reduce the suspended solids content of stabilization pond effluent from 119 mg/litre to zero.

The reclamation of sewage effluents for domestic use as envisaged by Cillie, van Vuuren et al (64) depends on successful stripping of nutrients by algae. Since subsequent algal removal is equally important in order to prevent filter blockage and excessive chlorine demand, the reclamation process demanded the development of a satisfactory method for harvesting the algal culture. This was achieved using a flocculation-flotation system based on the photosynthetic oxygen supersaturation of algae-laden water. Aluminium sulphate flocculant was added immediately prior to pouring the algal pond effluent into the flash-mixing compartment of a flotation unit. All salient pollutants were reduced satisfactorily and significant reductions of bacteria, probably by adsorption on the floc, were obtained. The entire operation was accomplished in a relatively small and simple tank with retention times as short as 6.5 minutes.

Similar investigations have been made by McGarry and Durrani (65). They have evaluated dissolved-air flotation in the laboratory as a unit process in a sewage treatment programme designed for pollution control, water reclamation and algal protein production. Algae-laden high-rate oxidation pond water was used as a raw water supply to a laboratory-scale dissolved-air flotation unit employing a down-flow solids contact principle. Optimum performance in the flotation unit was obtained using an aluminium sulphate dose of between 125 and 145 mg/litre and with pH adjustment to between 5 and 7.

They reported that float solids concentrations greater than 7% were possible with retention periods as low as 6 minutes in the flotation unit. Problems encountered with the apparatus were turbulence due to the inflowing water and build-up of large air bubbles in the influent tube during conditions of low flow. Both effects hindered flotation and it was recommended that consideration should be given to these problems when designing flotation units.

4.3. Water clarification

The clarification of water by flotation was proposed by Hopper (66) who suggested that the method was suitable for the removal of suspended and colloidal matter from raw surface waters. He investigated raw water from 34 different surface sources, employing a surface-active agent for foam flotation, and obtained average reductions of 70% in turbidity, 79% in suspended solids and approximately 90% in bacterial plate counts. Hopper and McGowen (67) continued this work using various quaternary ammonium compounds as collector. They concluded that raw water of turbidity from 15 to 300 mg/litre could be purified by foam flotation. Using 10 mg/litre of a non-toxic quaternary ammonium compound it was found that less than 1 mg/litre would remain after treatment. A reduction of up to 99% in the bacteria count could be achieved and the costs involved (without chlorination) would be approximately 1.3 U.S. cents per m^3.

A foam flotation unit for water clarification was reported by Grieves (68) (Fig. 2), who investigated the use of a cationic surface-active agent (ethylhexadecyldimethyl ammonium bromide, EHDA-Br) for the removal of turbidity from low quality raw water supplies. The cationic surface-active agent was adsorbed onto the negatively-charged colloidal-size particulates which could then be floated to the surface by aeration. Results are given for approximately 200 batch flotation experiments to remove synthetic turbidity from synthetic raw waters. In addition, the effects of pH and of the presence in the water of mono and divalent cations and anions, of trivalent cations and anions and of organics were investigated. The foam flotation process described was stated to have promise for the clarification of low quality waters available to small municipalities or as a field raw water supply to the armed forces. A residual surfactant concentration of less than 4.0 mg/litre was estimated which, it was claimed, should provide no difficulty, particularly as this could be readily reduced to less than 0.5 mg/litre by activated carbon adsorption.

Preliminary cost estimates for small units operated on a discontinuous basis, and including the air, the cationic surfactant and the active carbon, would be 9.3 U.S. cents per m^3 of raw water containing 125 units of turbidity, and 4 to 5.3 cents per m^3 of raw water containing 50 units of turbidity. Most of the bacteria were successfully removed by the foam flotation process and it was pointed out that the quantity of disinfectant normally required would be decreased, as cationic surfactants are themselves disinfectants.

Grieves and Schwartz (29) later reported the development of a continuous foam flotation unit which was used to investigate the effects of retention time, surfactant concentration in the feed, use of bentonite as a flotation aid, temperature, air rate, pH of the feed, and the presence of organics in the feed upon the continuous flotation of five synthetic turbidity constituents. With regard to residual surfactant removal by activated carbon, it was found that approximately 40 m^3 of water could be treated for complete surfactant removal per kg of carbon, based on continuous flow column studies with a feed concentration of 2 mg/litre. It was shown that, compared with batch foam flotation experiments, higher surfactant concentrations and longer aeration times were required with continuous flow operation - 50 mg/litre surfactant and 80 minutes retention against 30 mg/litre surfactant and 30 minutes retention - to obtain comparable results.

With other workers, Grieves has investigated the use of the foam flotation process on aqueous suspensions of clays and/or iron (69), as a model for waste treatment applications (70), and for water clarification using bentonite as a flotation aid (71).

The application of dissolved-air flotation techniques for the clarification of raw surface waters appears largely to have been neglected, the only published work found on this subject being a recent report by Uden and Karlstrom on the new waterworks in Skagersvik, Sweden (72). Because the established sedimentation plant at Skagersvik was affected by summer algal blooms, it was decided that a flotation unit should be constructed when the plant was extended. This plant, capable of treating 2 400 m^3/day at a capital cost of approximately £412 000, was built in eight months, and comprises flocculators and two rectangular flotation tanks each provided with a sand filter at the base, (UK Pat. No. 1,184,477). These tanks sequentially float and filter precoagulated water in one continuous operation, employing a 10% recycle of water saturated with air at 5 atmospheres. The layer of floated sludge is removed by closing the treated water outlet or by backwashing the sand filter - in both cases the water level rises and the sludge (and some water) flows into troughs. Water losses of approximately 1.25% during sludge removal and 1% during backwashing are reported.

The quality of the treated water is said to have improved since the introduction of this plant and water losses, often 5-6% during sedimentation, have dropped to 2.5%. Furthermore, filter runs are at least three times as long with flotation, reflecting its efficiency as a separation process. Chemical costs appear to be the same as with sedimentation and the energy requirements of the treatment plant are approximately 0.1 kWh/m^3 of product water. It is claimed that 2 to 3 hours per day suffices for plant maintenance. No analytical results for the raw and treated water are given.

Thickening of sludge resulting from water clarification using dissolved-air flotation has been reported by Albrecht (39). This he considered to be a promising method for concentrating alum sludges from water treatment plants. In laboratory experiments he found that raw alum sludge responded poorly to flotation, the sludge particles remaining dispersed throughout the test cylinder. However, after addition of an anionic polymer, the sludge thickened well forming a distinct floated layer of 1.6% solids content. The rise rate was approximately 20 mm/sec and the treated sludge liquor was mainly clear with little material left in suspension. Sludge floated in this manner was found to be very unstable and was easily dislodged by tapping on the wall of the cylinder. It was therefore concluded that this type of sludge would present handling problems if produced in conventional flotation plant.

In the absence of a polymer, acidified alum sludge also exhibited poor flotation characteristics. Dosing a cationic polymer at 8 mg/litre produced a stable floated sludge layer of 4% solids concentration, with a rise rate greater than 35 mm/sec. The remaining water was again clear.

4.4. Results obtained using flotation

Table 1 summarizes the suspended solids removal performances of some of the methods of flotation applied to various waters.

5. THE POTENTIAL OF FLOTATION PROCESSES IN WATER TREATMENT

This review has shown that the flotation process is very flexible and has been adapted to meet a wide variety of requirements. In no field is it more advanced than in mineral processing, the dominant example of an industry heavily dependent on flotation processes. For those concerned with water treatment however, the technology developed for mineral flotation is largely of only academic interest; there are many reasons why the requirements of water treatment and mineral processing are completely different. Because of this, the wealth of information available on mineral flotation has not been considered in any detail in this review.

In the field of waste water and effluent treatment the development of flotation is at an early stage; in water clarification it has been almost completely ignored. The requirement here is for a low-cost process capable of dealing with high throughputs of water (0.1 m^3/sec and more) containing a low concentration of suspended solids. These are in the form of a fragile floc that disintegrates into particles of colloidal dimensions if subjected to high rates of shear. The addition of costly reagents or substances likely to affect adversely the 'wholesomeness' of water is undesirable.

There are several different types of flotation process available; perhaps the most basic difference is that between the dispersed-air and the dissolved-air processes. Which of these would be most suitable for use in water clarification? Although a number of investigators in the United States have made detailed studies of dispersed-air flotation, we believe that for water treatment the advantages of dissolved-air flotation are too weighty to merit serious consideration of the alternative.

Perhaps the most important advantage is the fact that many solids can apparently be floated using dissolved-air without the addition of a surface-active agent. In dispersed-air flotation, a surface-active agent is usually required and in water clarification this leads to a considerable increase in costs, not only due to the reagent but also due to the necessity to provide for its removal from the treated water (29). In addition, the floated phase is separated as a froth instead of a viscous sludge.

TABLE 1

FLOTATION - REMOVAL PERFORMANCES ON VARIOUS INDUSTRIAL WASTES, SEWAGE SLUDGES AND OTHER WATERS

Method of flotation	Species investigated	Influent s. s. (mg/ litre)	Effluent s. s. (mg/litre)	% Removal	Remarks if any	References
Dissolved air	Soybean processing waste	1656	42	97.5	Using alum, $Ca(OH)_2$ and various polyelectrolytes	
"	Potato processing waste	2600	60	99.7		
"	Tomato processing waste	172	59	65.7		
"	Beet processing waste	5050	11	99.8		
"	Chicken processing waste	1690	275	83.7		
"	Cosmetic and toiletries waste	15000	1800	88.0		
"	Laundry waste	3469	281	91.9		
"	Porkskin tanning waste	7792	1310	83.2		(27)
"	Slaughterhouse wastes	700	1	~100		(19)
"	Motor manufacturing wastes	1941	35	98.2		(73)
"	Glue manufacturing wastes	542	30	94.3		(24)
"	Tissue paper mill waste	1000	30	97		(74)
"	Pulp and paper waste	3000	76	97.6		(25)
Froth flotation	Paper mill waste	586	12	98		(43)
"	Sewage and dye waste	222	4	98.3		(43)
Dispersed air	Toilet tissue waste	130	1.2	99		(8)
Dissolved air	Algae	110	0	100		(20)
Dissolved air (Belleville Ill.)	Sewage sludges	18370	233	98.7		(73)
Dissolved air (Bernardsville, N. J.)	Sewage sludges	3600	200	94.5	Without flotation aids	(73)
Dissolved air Nassau Co. N. Y.)	Sewage sludges	7600	860	94.0		
Dissolved air (Nassau Co. N. Y.)	Sewage sludges	8100	36	99.6	With flotation aids	(73)
Dissolved air (Omaha, Neb.)	Sewage sludges	19660	118	99.8		(73)
Dissolved air	Sewage sludges	2640	4	~100		(25)
Micro-flotation	Organic colloids (<u>E.coli</u>)	-	-	99	pH 7.3	(58)
Froth flotation	Harvesting algae	-	-	98		(30)
"	Polystyrene balls, 259 nm in dia.	-	-	>95		(67)
"	S.S. in raw surface waters	-	-	79		(66)

Dissolved-air flotation can be achieved without the addition of any obnoxious chemicals. It is less selective and does not involve any violent agitation which could result in floc breakdown. Individual units with a capacity of up to 0.08 m^3/sec have been constructed to deal with industrial waste and there is no obvious reason why the construction of larger units should present difficulty.

There is reasonable evidence that the capital cost of flotation installations is lower than that of sedimentation plants of the same capacity. Kalinske and Evans (74), for example, refer to overflow rates of 2 to 4 mm/sec obtainable with flotation compared to 0.3 to 1.3 mm/sec with sedimentation. These high rates of treatment, suggesting significant capital savings, are amply confirmed by the findings of other workers. The introduction of air in flotation leads, however, to a higher power consumption than for sedimentation. Power costs as high as £1000 p.a. for a 0.04 m^3/sec plant have been reported (74) for a dissolved-air flotation plant in which the total flow is pressurized to 172 kN/m^2 (25 $lb/in.^2$). It has been pointed out however (26) that this cost could be reduced by 25 to 50% using the more efficient technique of effluent pressurization (Sect. 3.2.)

Capital costs for a 0.02 m^3/sec dissolved-air flotation system designed for treating effluent from food factories and poultry processing plants have been quoted (75) as between £12 000 and £15 000. Running costs, mainly for labour and electrical power were of the order of £10 to £15 per week.

It has been shown (76) that for the treatment of storm water and sewer overflows, the total annual costs for dissolved-air flotation systems are less than costs for conventional clarifiers for flows up to 0.4 m^3/sec. For flows in excess of this figure conventional clarifiers show lower total annual costs for, as the capacity is increased, the operation and maintenance costs become very significant in the dissolved-air flotation process. However, depending on site land costs, further savings may accrue to flotation systems, as these may require only one-tenth of the land area occupied by conventional clarifiers. Further space conservation is possible as flotation tanks may be stacked two high.

There are other areas in which the use of flotation could have a beneficial effect on overall costs. There is good evidence that algae can be separated from water very effectively by flotation. In situations where algal blooms are a serious problem the use of flotation could lead to savings derived from lower coagulant doses and longer filter runs. Another possible benefit is the production of a sludge having a higher solids content than conventional settled sludge. Unfortunately while these advantages may be inferred from experience with flotation in a number of applications no definitive data exist for water clarification and there is a clear need for more work in this field.

6. CONCLUSIONS

- Flotation can be an efficient and versatile method of solid/liquid separation. Its use in water clarification as an alternative to sedimentation has not been considered to any great extent.
- Possible advantages of flotation over sedimentation include improved removal of algae, lower capital costs and the production of sludge having a higher solids content.
- For water clarification, dissolved-air flotation has a number of significant advantages over other flotation systems and warrants particular consideration.
- Research should be undertaken to determine the efficacy of dissolved-air flotation under a variety of conditions, the main factors affecting operation and an estimate of the likely costs.

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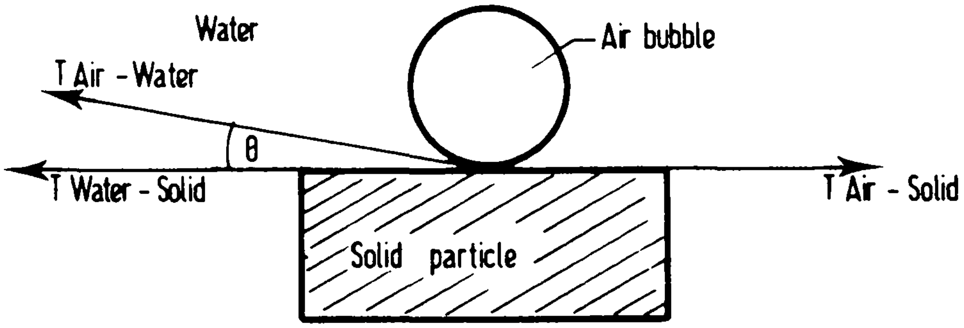
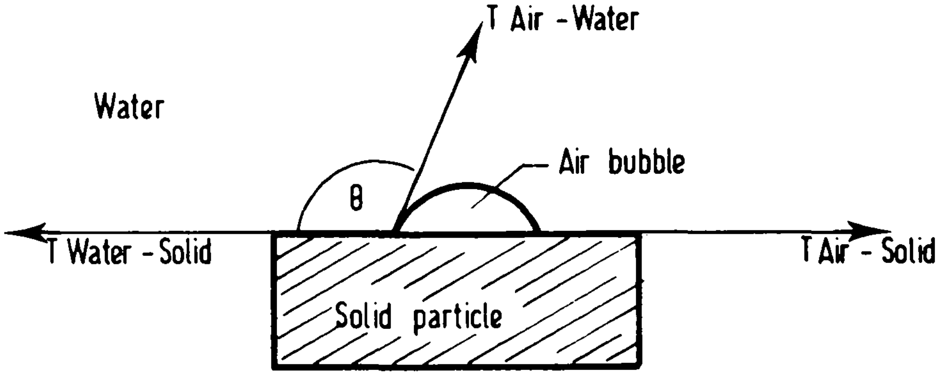


(a) SMALL ANGLE OF CONTACT - POOR BUBBLE ADHESION



(b) LARGE ANGLE OF CONTACT - GOOD BUBBLE ADHESION

FIG. 1. CONTACT ANGLES BETWEEN A BUBBLE AND A DISPERSED PARTICLE.

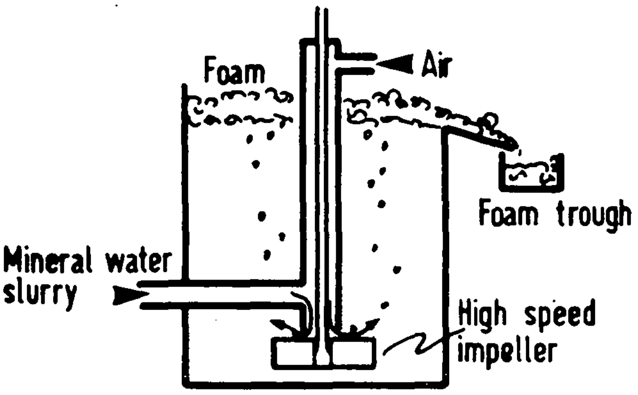


FIG. 2 MECHANICAL - FROTH FLOTATION OF MINERALS.

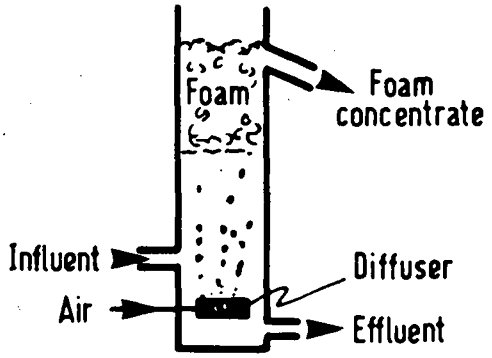


FIG. 3. PNEUMATIC - FOAM FLOTATION COLUMNS.

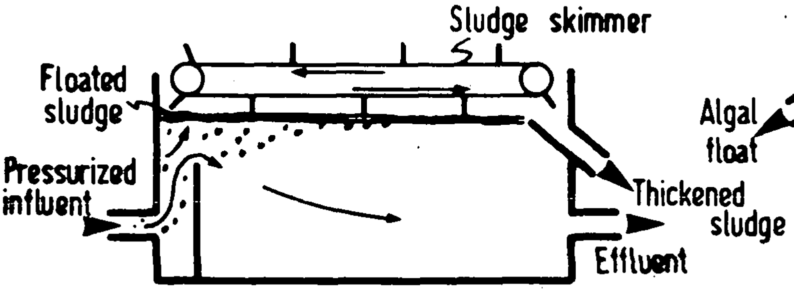


FIG. 4. DISSOLVED AIR FLOTATION -for sewage sludge thickening (mainly U S A).

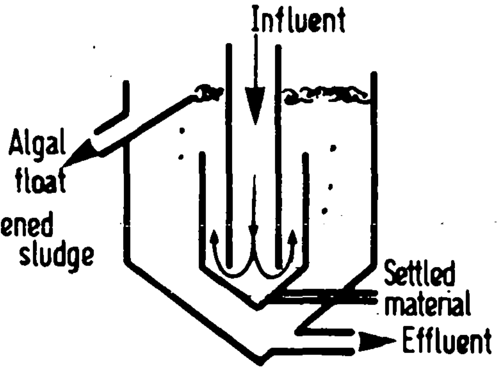


FIG. 5. DISSOLVED / DISPERSED AIR FLOTATION - for algae (South Africa).

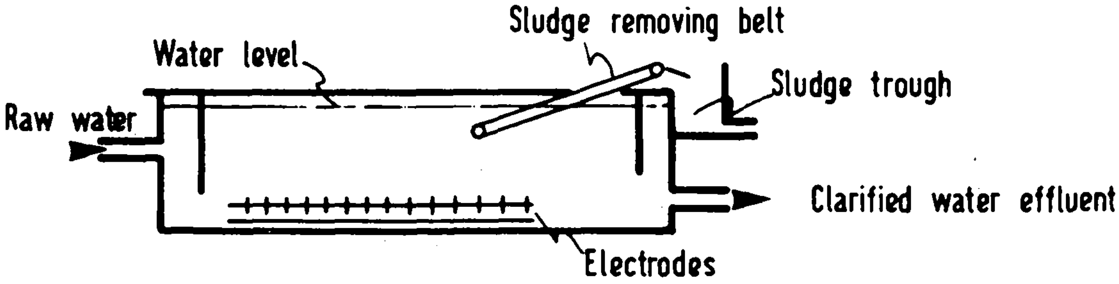
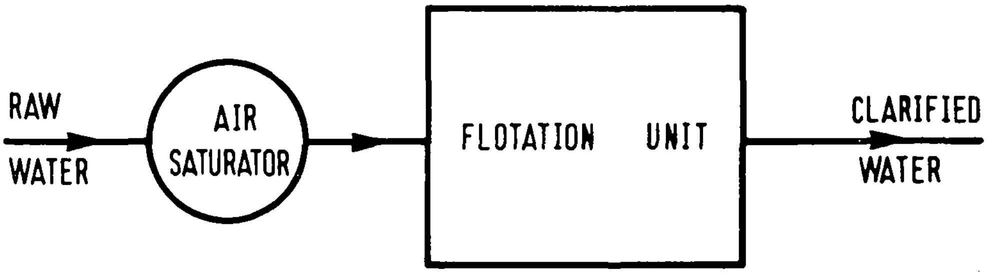


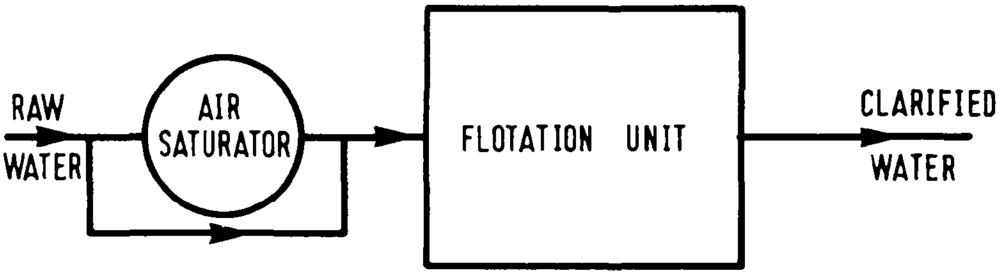
FIG. 6. ELECTROLYTIC FLOTATION

TYPES OF FLOTATION PLANT.

(a) Total influent pressurization



(b) Partial influent pressurization



(c) Partial effluent pressurization

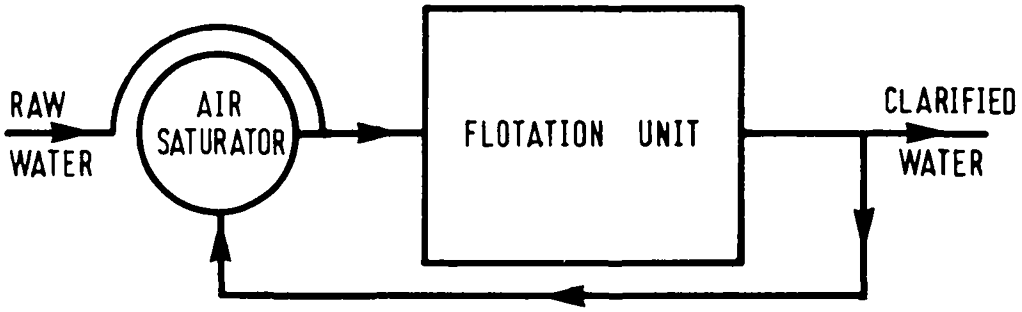


FIG. 7. AIR SATURATION.