- De-sanding hydrocyclones are now being installed upstream from the choke in some fields. There could be an energy saving if de-sanding and de-oiling could be performed in a single unit, but simultaneous optimization of both functions is unlikely. A successful laboratory research project has been reported in France, but initial field trials in West Africa were disappointing.
- Heavy oils, i.e. those with a higher density and viscosity, appear unpromising for cyclonic separation processes. Nevertheless success has been reported for commercial de-oiling units used in the concentrator mode in trials in western Canada.
- Feasibility studies and preliminary field trials are in progress on integrated de-watering plus de-oiling cyclonic separation and/or de-sanding plus de-oiling. The attraction is an ultra-compact plant suited particularly to floating installations. Though de-watering units have not yet met with widespread success, the impending arrival of compact, robust electrocoalescers to raise water droplet size prior to separator entry, could transform the situation.
- With success in dealing with petroleum it is surprising that applications to edible oils, which are about 10 times more valuable, have yet to materialize. Laboratory trials have been very satisfactory. Not only is lost oil a revenue drain but it generates a potential environmental hazard.

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Note: The five conferences on hydrocyclones all contain several papers on oil–water hydrocyclones

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Dissolved Air

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Introduction

Dissolved air flotation (DAF) is a solid–liquid separation process for the removal of fine suspended material from an aqueous suspension. The basic principle underlying DAF is Henry's law, which gives the solubility of air in water. According to Henry's law, the solubility of air in water is directly proportional to its partial pressure. A supersaturated solution of water is produced using high pressure in a saturator. The bubbles are generated by the pressure release of this water stream. These bubbles attach to suspended material present in the aqueous stream, causing them to float to the surface, where they are collected as floc.

DAF can be carried out by vacuum or pressurized methods. In the vacuum flotation method the water to be treated is saturated with air at atmospheric pressure. The bubbles are produced by applying a vacuum to the flotation tank, releasing the air as fine bubbles. The vacuum flotation process has several disadvantages. These are (a) the amount of air available for flotation is limited by the vacuum achievable, (b) it is a batch process, and (c) it requires special equipment to produce and to maintain high vacuum. These disadvantages limit the application of vacuum flotation and it is only used in wastewater sludge thickening.

The pressure flotation process is the most widely used DAF technique. High pressure water is saturated with air. This pressurized water forms small bubbles when injected into water at atmospheric pressure. Three types of pressurization processes can be used in DAF: full flow, partial flow and recycle flow pressurization. The entire inlet stream is pressurized in full flow pressure DAF. It is commonly used when the wastewater contains large amounts of suspended solids and the pressurization process does not affect the treatment efficiency of the system. Partial flow pressurization is used where the wastewater contains moderate to low concentrations of suspended solids. In the recycle flow pressurization system, 10–25% of the clarified effluent is recycled through a pressure vessel to the flotation tank. The flocculation process in not disturbed in the recycle flow system because of intense mixing and pressurization as clear water is pumped. A recycle flow system is cost-efficient because it pressurizes only part of the water, thus requiring less compressor power. Recycle flow pressure flotation is the best-suited system for most DAF applications.

DAF is an effective alternative to sedimentation. The advantages and disadvantage of DAF relative to sedimentation are as follows:

Advantages

1. Clarification rates are higher in DAF, resulting in smaller flocculation tank volumes.
2. More concentrated sludge solids are produced in DAF than from sedimentation.
3. DAF uses lower amounts of coagulants and flocculent aids.
4. Oxygenation effects in DAF reduce odour problems.
5. DAF provides better removal of low density particles and algae, which can plug filters.

Disadvantage

1. DAF processes are more costly to operate and maintain than sedimentation processes.

Process Description

A schematic diagram of a DAF process for wastewater treatment is shown in **Figure 1**. Its essential elements are a flocculation tank, a flotation tank, an air compressor, an air saturator, a recycling pump and a hydrosweep system. The wastewater is pumped to the flocculation tank after being treated with coagulant/flocculent agents such as aluminium sulfate. A portion of the clarified effluent is recycled for pressurization. Compressed air is introduced into the discharge stream of the recycle pump, and the water is saturated with air at high pressure. The pressurized water stream is introduced to the flotation tank through nozzles, where fine bubbles (20–100 μm) in diameter are formed. The bubbles attach themselves to suspended solid particles, causing the agglomerates to float to the surface of the tank. The float can be mechanically skimmed from the surface, and the clarified water is taken from the bottom of the flotation tank.

Principles of Dissolved Air Flotation

DAF facilities are composed of the following four principal steps:

1. coagulation and flocculation prior to flotation
2. bubble generation
3. bubble–floc collision and attachment in the mixing zone
4. rising of the bubble–floc aggregates in a flotation tank

Coagulation and Flocculation Prior to Flotation

Coagulation and flocculation are often considered as a pretreatment step in DAF processes. Favourable

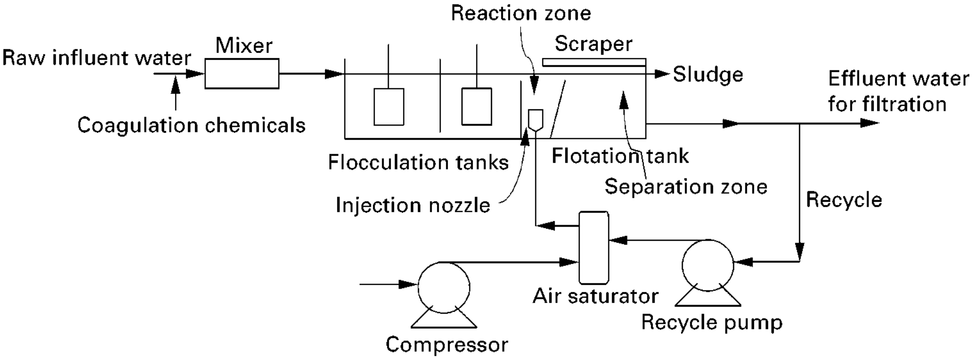

Figure 1 Schematic diagram of the dissolved air flotation process for water treatment.

conditions for bubble attachment to particles requires coagulation conditions that reduce particle charge and produce hydrophobic particles. Coagulant dosages and pH conditions that satisfy these criteria depend on the coagulant type and raw water characteristics, including particle concentration, hardness, and concentration and type of natural organic matter (NOM). Unlike in sedimentation, large floc particles are not needed in DAF. Flocculation tanks are designed to produce strong flocs with particle size distributions of 10–30 μm and short flocculation times, in the range of 10–15 min.

Bubble Generation

Small air bubbles, 100 μm or less, are formed by injection of supersaturated pressurized recycle water into a flotation tank using specially designed nozzles. The process of bubble formation involves two steps: nucleation and growth. During the first step the large pressure difference across the nozzle produces bubble nuclei spontaneously. Air bubbles grow at a fixed number of nucleation centres due to air transferred from the water. As the excess air is transferred from the dissolved to the gas phase, the bubbles grow in size. Additional bubble growth may occur as the bubbles rise due to a decrease in hydrostatic pressure or coalescence.

Measurements of bubble sizes for DAF systems indicate that bubbles maintain a steady-state size range of 10–100 μm. A reasonable estimate of average bubble diameter is 40 μm. The steady-state size depends on the saturator pressure and the injection flow rate. The injection flow must provide a rapid pressure drop and be sufficient to prevent backflow and bubble growth on pipe surfaces in the vicinity of the injection system. To ensure small bubbles, pressure differences (saturator gauge pressures) of 400–600 kPa are recommended.

Bubble Floc Collision and Attachment in the Mixing Zone

There are three possible mechanisms for forming aggregates of bubbles and particles:

1. entrapment of preformed bubbles in large floc structures (floc size much larger than bubble size scale)
2. growth of bubbles whose nuclei formed on particles or within flocs
3. particle collision with adhesion to preformed bubbles

For DAF processes, the third mechanism is the most important.

Classically, the contact angle between the adsorbed bubble and particle has been used to characterize the extent of bubble–floc adhesion. Here the contact angle must be finite and large enough that the energy of adhesion of water to the solid particle is less than the energy of cohesion of water. A larger contact angle indicates both hydrophobicity and good adhesion. The magnitude of the contact angle, however, depends on the size of the bubbles and particles. A different view of particle–bubble attachment of colloidal particles by small bubbles is that a finite contact angle need not form. In this heterocoagulation model, the stability of charged particles and bubbles is described. Attachment requires reduction in electrical charge interactions and attraction by London–van der Waals forces as particles are transported to bubble surfaces.

Both the contact angle and the heterocoagulation models predict experimentally observed trends that two conditions are necessary for favourable flotation: charge neutralization of the particles and production of hydrophobic particles. Bubble attachment to particles requires hydrophobic particle surfaces or hydrophobic regions on the particles. For many particles, hydrophobicity can be increased by reducing the negative charge. Other particles, such as freshly precipitated or amorphous $Al(OH)_3$, have polar surface groups that make them hydrophilic. This hydrophilic effect may be reduced by charge neutralization, but aluminium hydroxide particles have a polymolecular coating of water which hinders bubble adhesion.

Rising of the Bubble–Floc Aggregates in a Flotation Tank

Following bubble attachment and reduction in particle density, particle–bubble agglomerates rise to the surface of the flotation tank in the separation or clarification zone. The rise velocity of the particle–bubble agglomerate may be calculated using Stokes law.

DAF Modelling

The design and operation of DAF facilities has largely been based on experience and results from pilot-plant studies. In recent years, a conceptual model of DAF has been developed, based on a single collector collision theory in laminar flow conditions (SCC model). A kinetic model has also been presented, based on the population balance model of bubbles and flocs in a turbulent flow condition (PBT model).

For modelling purposes, DAF processes can be divided into two zones: reaction zone (regions where the saturated recycle flow is introduced) and separation zone.

Reaction Zone Modelling

For the reaction zone efficiency ($\mathrm{d}N_{\mathrm{fl}}/\mathrm{d}t$), defined as the reduction of number of primary particle flocs with time, floc and bubble size (d_{fl} and d_{b}) and concentration are defined as relevant process parameters:

$$\mathrm{d}N_{\mathrm{fl}}/\mathrm{d}t = -(3/2)(\alpha_{\mathrm{pb}}\eta_{\mathrm{T}})(\Phi_{\mathrm{b}}v_{\mathrm{b}}N_{\mathrm{fl}})/d_{\mathrm{b}} \qquad [1]$$

where α_{pb} = particle bubble attachment efficiency; η_{T} = total single collector efficiency; d_{b} = bubble diameter; v_{b} = bubble rise velocity; N_{fl} = floc number concentration; Φ_{b} = bubble volume concentration.

Particle (floc)–bubble interception is considered to be the most relevant kinetic mechanism for DAF efficiency, depending on the floc and bubble size (d_{n} and d_{b}) and incorporated in η_{T}. This term also considers floc–bubble collision mechanisms related to Brownian diffusion, settling and drag.

A summary of these parameters, their dependence on the system variables and desirable operational conditions is given in **Table 1**.

Separation Zone Modelling

Assuming laminar flow conditions, the efficiency of the separation zone, v_{flb} (defined as floc–bubble agglomerate rising velocity), is defined by the floc–bubble agglomerate size (d_{flb}) and density (ρ_{flb}) (eqn [2]). These are dependent on the floc size–density ratio and concentration, and the size and number of bubbles comprising the floc–bubble agglomerate:

$$v_{\mathrm{flb}} = g d_{\mathrm{flb}}(p_{\mathrm{w}} - p_{\mathrm{flb}})/18\,\mu \qquad [2]$$

Eqn [3] represents a necessary prerequisite for efficient DAF, v_{os} being the DAF overflow rate and m being the fraction of DAF tank dead space:

$$v_{\mathrm{flb}} > v_{\mathrm{os}}/(1 - m) \qquad [3]$$

Applications of Dissolved Air Flotation

DAF is best applied to remove materials that normally settle slowly, persist in remaining in suspension or have a tendency to float. Prior to the 1960s it was mainly utilized in the area of mining and metallurgical industries. Now, DAF finds numerous applications, e.g. mineral processing, water purification, wastewater treatment, waste sludge thickening, wastewater reclamation, recycled paper de-inking, and many more. It is widely used for drinking water purification in many Scandinavian countries, South Africa, the Netherlands, the UK and others. In drinking water clarification, DAF has been applied in combination with flocculation for the removal of

Table 1 Summary of conceptual reaction zone model parameters

Parameter	*Dependence*	*Comments*
Pretreatment parameters		
α_{pb} (particle–bubble attachment efficiency)	1. Particle–bubble charge interactions	1. Favourable flotation; requires reduction in particle charge and hydrophobic particles
	2. Hydrophilic nature of particles	2. Increase α_{pb} to 1: optimum coagulation and charge neutralization
N_{p} (particle number concentration)	1. Raw water quality	1. Concentration and size of particles; concentration of NOM
	2. Coagulant type and conditions	2. Coagulants may add particles
	3. Flocculation time	3. Flocculation may reduce N_{p} and increase d_{p}
Reaction zone–flotation tank		
η_{T} (total single collector efficiency)	1. Particle–bubble collisions from diffusion and interception	1. Increase η_{T} : produce floc size of tens of μm
	2. Minimum η_{T} for d_{p} of ~1 μm	2. Short flocculation times
d_{b} (bubble diameter)	Controlled by pressure difference across nozzle and injection flow	1. Desire microbubbles: range 10–100 μm, median 40 μm; smaller bubbles: better performance
		2. η_{T} varies as d_{b}^{-2}; rate of collection of particles varies as d_{b}^{-1}
Φ_{b} (bubble volume concentration	1. Saturator pressure	1. Increasing Φ_{b} increases N_{p}: more bubbles for collection of particles
	2. Recycle ratio	2. Increase Φ_{b}: more bubble volume for reducing floc density

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algae and humic substances. The first water treatment plant based on the DAF process was established in South Africa in 1969. Since then it has received worldwide attention for research and development on all aspects of DAF.

The first DAF plant in the USA was set up at the Millwood water treatment plant in Westchester county (35 miles north of New York city) in August 1993. Now, several other plants based on DAF are operating or are under study in the USA. It is postulated that DAF is an emerging technology in the USA that will become more important because of existing and proposed regulations that require filtration of surface waters and increased removal of protozoa cysts such as *Cryptosporidium* and *Giardia*. Large scale pilot-plant trials of water treatment have been carried out in the UK for removal of *Cryptosporidium* using DAF. Well-operated chemical coagulation-based treatment using DAF should be capable of achieving 99% removal of *Cryptosporidium* oocysts.

DAF is also used in the forest industry, foodstuff industry, meat-processing industry, seafood industry, potato processing, pulp and paper industry, petroleum industry, poultry industry, producing refined sugar from raw juices, separation of grease, oil, fibres and other low density solids, chemical processing plants, storm water cleaning, and other similar industries.

Future Trends

There is great potential for DAF. Its use has been limited due to lack of knowledge of the process by users, designers and other regulatory agencies. The design and operation of DAF methods are currently tested on empirical data and data from costly and time-consuming pilot-plant models. More information is needed on the performance, designs and costs of the DAF process.

See also: **I/Flotation.**

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Electrochemistry: Contaminant Ions and Sulfide Mineral Interactions

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Introduction

Mineral separation by flotation is based on the selective levitation and separation of mineral particles by gas bubbles. This is carried out by the selective conversion of the surfaces of the minerals to be floated from their typical hydrophilic nature to hydrophobic, to which the gas bubbles may attach to effect the levitation. This conversion is usually achieved by the selective attachment of collectors to the surface of the mineral or by natural processes; an example of the latter is the formation of elemental sulfur or a metal-deficient sulfide layer on sulfides.

Typical collector agents are organic substances consisting of an ionic, i.e. hydrophilic, end that attaches to the mineral and a nonionic hydrocarbon end that creates the hydrophobicity of the mineral surface. A widely used collector in selective sulfide flotation is the xanthate ion (O-alkyldithiocarbonate, $ROCS_2$).