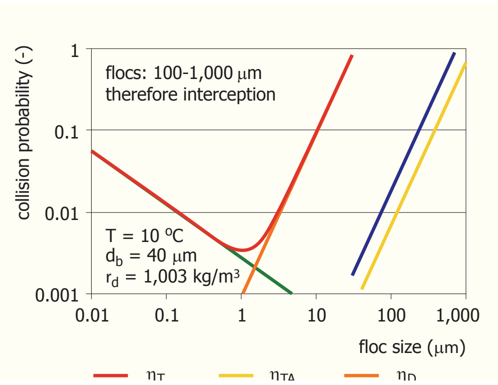
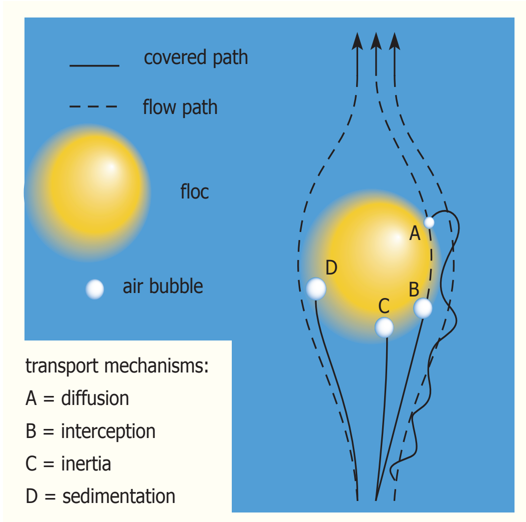
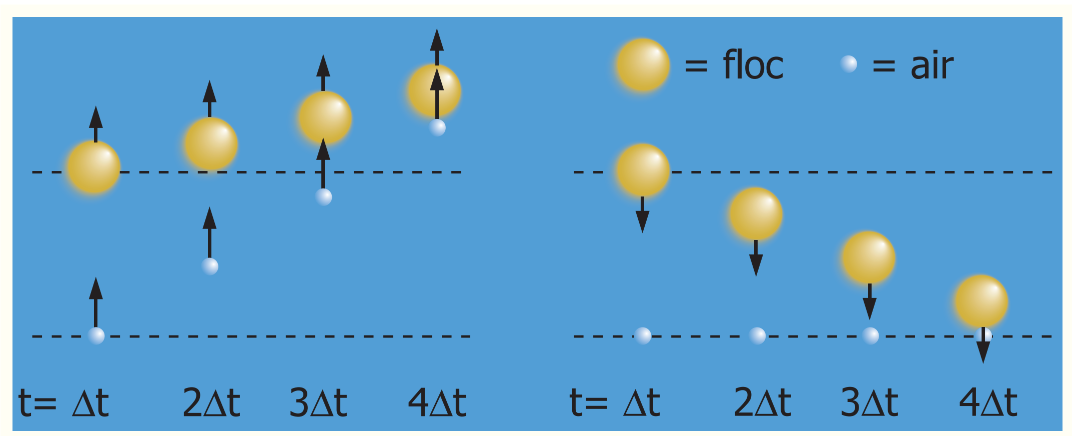
WATER TREATMENT

Flotation







Framework
This module explains flotation

Contents
This module has the following contents:

1 Introduction

In the past, flotation was mainly used as a floc removal process in the Scandinavian countries and the UK.
Zevenbergen (Brabant Water) was the first Dutch treatment plant to make use of that process (1979). Other treatment plants where flotation is applied are Braakman (Evides), Elsbeekweg Enschede (Vitens) and Scheveningen (Dune Water Company South Holland).

Flotation is applied to remove flocs during surface water treatment and is preceded by floc formation (flocculation).
In the flotation process very small air bubbles are used to “air-lift” the flocs to the water’s surface.
The number and size of the air bubbles is the key factor for the upward velocity of the flocs, and thus for the separation efficiency of the process.
The upward velocity of the flocs is much higher than the sedimentation rate of these flocs. Therefore the surface load of flotation is also much higher, than the surface load for the sedimentation process.

Flotation is often selected as the floc-removal process for conditions which are less favorable for sedimentation:
- low temperature of the water, resulting in a reduced sedimentation rate due to increased viscosity
- high algae content in the water, resulting in a reduced sedimentation rate (algae might even float due to the release of oxygen during the night).

The air dosing level is an operation parameter which can be brought into compliance with varying operational conditions (temperature, viscosity, floc size , floc density).

2 Principle

The principle of flotation is shown in Figure 1.
The flocculated raw water is distributed at the bottom of the flotation tank and flows in an upward direction over the baffle.

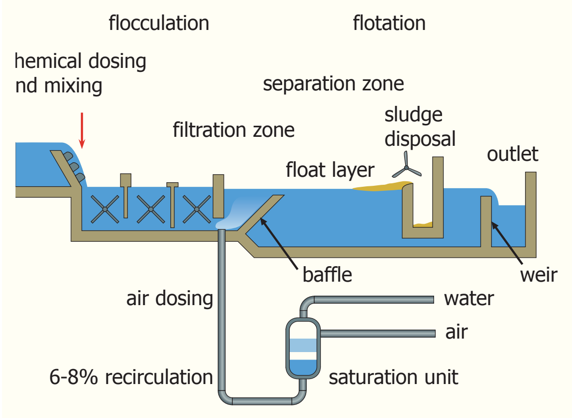


Figure 1 - Principles of floc formation and flotation

At the same time, a water flow with supersaturated air is supplied through nozzles. This water flow is called the saturation or recirculation flow. Due to the pressure drop in the supersaturated water at the nozzles, small air bubbles form.
The rising velocity of the air bubbles is greater than the water velocity, so the air bubbles collide with the flocs. Air pockets form beneath the flocs and the density of the aggregates decreases below the water density. As a consequence, the aggregates will float on the water’s surface.

Filtration zone

Schematically, the process in the zone before the above-mentioned baffle can be considered as a filtration process.
In Figure 2 a floc and an air bubble are represented in subsequent periods of time. It can be seen that the air bubbles rise faster than the flocs. Assuming the air bubbles are fixed (point of reference), the water moves with the flocs downwards and the flocs are filtered from the water by the air bubbles.

Separation zone

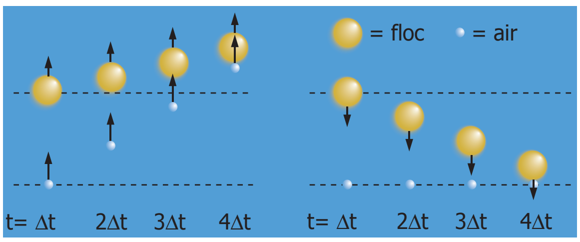


Figure 2 - Filtration principle during flotation

Figure 3 - Float layer in separation zone

Removal of the floating flocs takes place in the separation zone.
The flocs and the air bubbles form a float layer together at the water's surface (Figure 3).
The float layer is transported by the water flow to a weir and is drained. To accelerate the removal process of the float layer, rotors can be placed at the sludge overflow.
The treated water flows under the sludge removal device and over a weir to the outlet of the flotation system (Figure 1).
In some installations the weir of the float layer removal device is flexible. When the weir is high, the float layer is thin and there is a risk that water will flow into the sludge removal system. When the float layer is thick, the risk is that air bubbles will escape from the float layer and the flocs will start to settle.

The height of the weirs (water and sludge) is of primary importance to the performance of the flotation system.

Saturation unit
The saturation water is made by the saturation unit (Figure 4).
The saturation unit is supplied by a water flow and an air flow.
The water flow is about 6% - 8% of the total water flow through the treatment plant and is abstracted downstream of the flotation process. The water is pumped into a pressure vessel, at a pressure of 4 to 8 bar.
Air is supplied to the pressure vessel via an air compressor. Because of the high pressure, more

Figure 4 - Saturation unit

air can be dissolved than is possible under atmospheric circumstances.

The supersaturated water flow is transported from the saturation unit to the filtration zone and

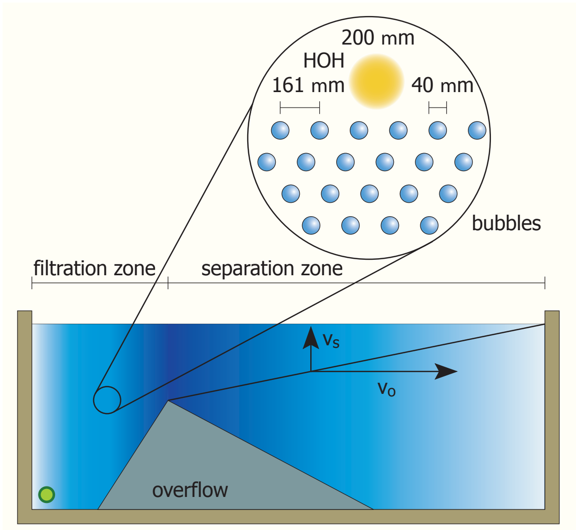


Figure 5 - Size and distance between bubbles and flocs

Table 1 - Specific parameters of air bubbles and flocs

Air bubbles			Flocs		
parameter	**value**	**unit**	**parameter**	**value**	**unit**
diameter	10 - 100	µm	diameter	100 - 200	µm
density	(1.5 - 3.0) ·10^{11}	bubbles/m^3	floc density	(2.5 - 19) ·10^7	flocs/m^3
distance between bubbles	150 - 188	µm	distance between flocs	3600 - 3700	µm
air dosage	5 - 10	l/m^3	density	1003 - 1006	kg/m^3
			particle concentration	10 - 25	g/m^3

inserted through the distribution nozzles.

Specific parameters

To give an idea of the order of magnitude of the air bubbles and flocs, some values that are encountered in practice are represented in Table 1.

Depending on the type of nozzle, the median diameter of an air bubble lies between 30 and 40 µm.
In Figure 5 some specific parameters determined at an air dose of 8 l/m^3 are represented.
From Figure 5 and Table 1 it can be concluded that collision between air bubble and floc is inevitable, because the distance between two air bubbles is smaller than the diameter of a floc.

3 Theory

3.1 Saturation unit for the supply of air

The amount of air that can be dissolved in a certain volume of water depends on the pressure and the water temperature and can be calculated with Henry's Law:

$$c_s = k_H \cdot c_a = k_H \cdot \frac{MW \cdot p}{R \cdot T}$$

in which:

c_s = saturation concentration of gas in water (g/m^3)
k_H = distribution coefficient (-)
c_a = concentration of gas in air (g/m^3)
MW = molecular weight of gas (g/mol)
p = partial pressure of gas in air (Pa)
R = universal gas constant = 8.3142 (J/(°K·mol))
T = (air) temperature (K)

When the concentration of gas in water is calculated with Henry's Law, the total air pressure can be used instead of the partial pressure. Then, the concentration c_a represents the specific density of air at the prevailing temperature and pressure.

In Table 2 the distribution coefficient for different air temperatures is represented.
By increasing the pressure, the amount of gas that can be dissolved in a volume of water increases proportionally, as is shown in Figure 6, where the saturation concentration is given as a function of pressure (atmospheric pressure at sea level is 101,325 kPa).

The gas exchange between water and air is more extensively explained in the module on aeration and gas stripping.

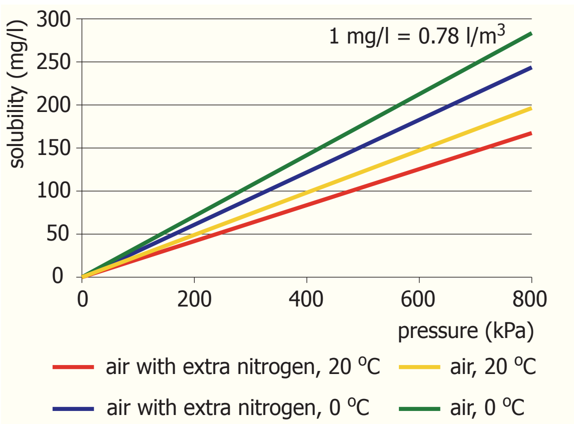


Figure 6 - Solubility of air in water

Table 2 - k_H-values at different temperatures and the molecular weight of air

Concentration of gas in air	T = 0°C	T = 10°C	T = 20°C	T = 30°C	MW [g/mol]
79% N_2, 21% O_2	0.0288	0.0234	0.0200	0.0179	28.84

3.2 Efficiency of the bubble filter in the filtration zone

The efficiency of a bubble filter in the filtration zone is equal to the proportion of flocs that collide with the bubble filter.
This portion of flocs can be derived from the mass balance, assuming a permanent attachment with one or more air bubbles.

Kinetics equation

In Figure 7 a plug flow is represented together with the principle of collision between flocs and air bubbles (see also Figure 2).
From the mass balance for a unit element dH (Figure 7), the kinetic equation for the collision of flocs and air bubbles in a plug flow can be derived.
The mass balance for a unit element dH is:

$$Q \cdot N_d dt = Q \cdot \left(N_d + \left(\frac{dN_d}{dH}\right) dH\right) dt + \text{c}$$

$$\text{x}_{db} \cdot \eta_T \cdot N_d \cdot N_b \cdot dV \cdot A_b dH$$

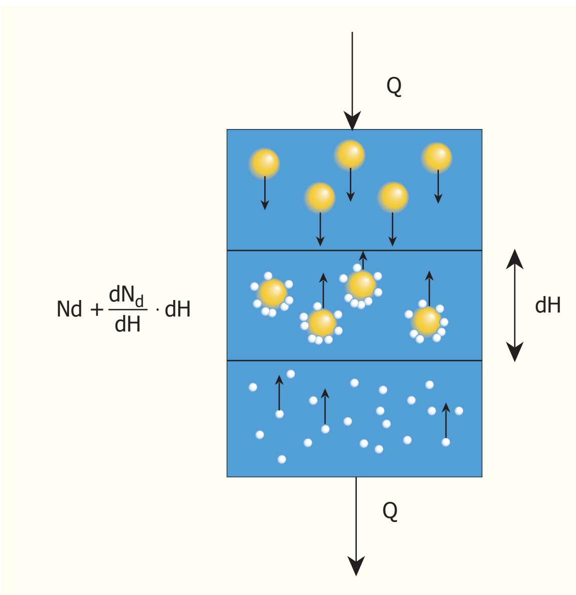


Figure 7 - Mass balance during filtration of the flocs

in which:

N_d = floc density (flocs/m³)
α_{db} = collision coefficient between air bubble and floc (-)
η_T = collision frequency between air bubble and floc (-)
N_b = air bubble density (air bubbles/m³)
dV = volume of unit element dH (m³)
A_b = projected area of an air bubble (m²/air bubble)

The second part of the right half of the equation represents the number of flocs that collide and attach to an air bubble in the unit element dH.
The number of flocs depends on the collision frequency, the collision efficiency, the number of flocs and bubbles in the unit element and the size of the projected collision area of the bubble.

The collision efficiency is determined by pre-treatment of the water and is negatively influenced by turbulence in the filtration zone. The collision frequency is elaborated on in section 3.3.
Rearranging the mass balance leads to:

$$\frac{dN_d}{dH} = -\alpha_{db} \cdot \eta_T \cdot N_d \cdot N_b \cdot A_b$$

with

$$dH = v_{db} \cdot dt$$

in which:

v_{db} = approaching velocity between air bubble and floc (m/s)

The kinetics equation for collision between air bubbles and flocs becomes:

$$\frac{dN_d}{dt} = -\alpha_{db} \cdot \eta_T \cdot N_d \cdot N_b \cdot A_b \cdot v_{db}$$

Because the air bubbles rise much faster than the

flocs, it is assumed that the approaching velocity is equal to the bubbles' rising velocity.
The rising velocity of an air bubble under laminar flow conditions can be calculated with Stokes' Law:

$$v_b = \frac{1}{18} \cdot \frac{g \cdot d_b^{\,2}}{\nu}$$

in which:

v_b	=	rising velocity of air bubbles	(m/s)
d_b	=	diameter of air bubbles	(m)
ν	=	kinematic viscosity	(m^2/s)

The air bubble density is equal to the air dosage divided by the volume of the air bubble:

$$N_b = \frac{\varphi_b}{\frac{1}{6} \cdot \pi \cdot d_b^{\,3}}$$

in which:

φ_b	=	air dosage	(m^3 air/m^3 water)

and A_b is:

$$A_b = \frac{1}{4} \cdot \pi \cdot d_b^{\,2}$$

Substituting v_{db} with v_b and inserting N_b and A_b gives the following kinetics equation:

$$\frac{dN_d}{dt} = -\frac{1}{12} \cdot \frac{\alpha_{db} \cdot \eta_T \cdot d_b \cdot \varphi_b \cdot g}{\frac{\nu_0}{v}} \cdot N_d$$

This equation is a first-order reaction and is equivalent to dc/dt = -kc in filtration and activated carbon filtration.

Efficiency
Under the assumption that the filtration zone can be schematized by a plug flow, the equation mentioned above can be integrated with the following boundary conditions:

- at t = 0: $N_d = N_{d,i}$
- at t = t : $N_d = N_{d,e}$

in which:

$N_{d,i}$	=	floc density of the influent	(flocs/m^3)
$N_{d,e}$	=	floc density of the effluent	(flocs/m^3)

After integration, the efficiency of filtration can be expressed as:

$$R = \frac{N_{d,i} - N_{d,e}}{} = 1 - e^{\left(-\frac{1}{12} \cdot \frac{\alpha_{db} \cdot \eta_T \cdot d_b \cdot \varphi_b \cdot g \cdot \tau}{\frac{\nu_0}{v}}\right)}$$

in which:

R	=	efficiency of a bubble filter	(-)
τ	=	residence time in the filtration zone	(s)

3.3 Collision probability between bubbles and flocs in the filtration zone

In the equation of the efficiency of filtration, the collision probability between air bubbles and flocs is incorporated.
The collision probability is the ratio between the actual number of collisions and the possible number of collisions between air bubbles and flocs.
It is assumed that the floc is situated in a water column above the air bubble with a surface area (perpendicular to the rising direction) equal to the projected area of the air bubble.

The four different removal mechanisms of filtration can be used to describe the collision between air bubble and floc:

- diffusion η_D, collision caused by Brownian motion of mainly small flocs and particles
- interception η_I, collision because the floc trajectory approaches the air bubble and interception of the floc by the air bubble is possible
- sedimentation η_S, collision caused by large and heavy flocs that deviate from the original trajectory
- inertia η_{TA}, collision caused by mainly large and heavy flocs that deviate from the curvature of the original trajectory.

For these transport mechanisms (Figure 8), the collision probability η or the Single-Collector Collision Efficiency (SCCE) can be quantified:

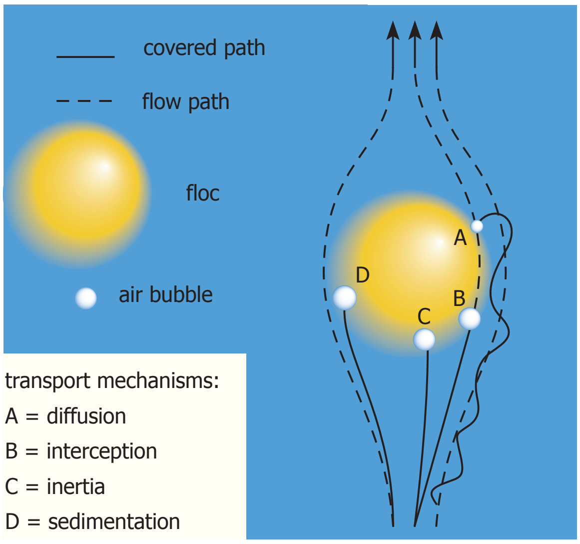


Figure 8 - Transport mechanisms

$$\eta_D = 6.18 \cdot \left(\frac{k_b \cdot T}{g \cdot \rho_w}\right)^{\frac{2}{3}} \cdot \left(\frac{1}{d_d}\right)^{\frac{2}{3}} \cdot \left(\frac{1}{d_b}\right)^2$$

$$\eta_I = \frac{3}{2} \cdot \left(\frac{d_d}{d_b}\right)^2$$

$$\eta_S = \left(\frac{\rho_d - \rho_w}{\rho_w}\right) \cdot \left(\frac{d_d}{d_b}\right)^2$$

$$\eta_{TA} = \frac{g \cdot \rho_d \cdot d_b \cdot d_d^{\,2}}{324 \cdot \nu \cdot \rho_w}$$

in which:

k_b	=	Boltzmann constant = $1.38 \cdot 10^{-23}$	(J/°K)
T	=	absolute water temperature	(°K)

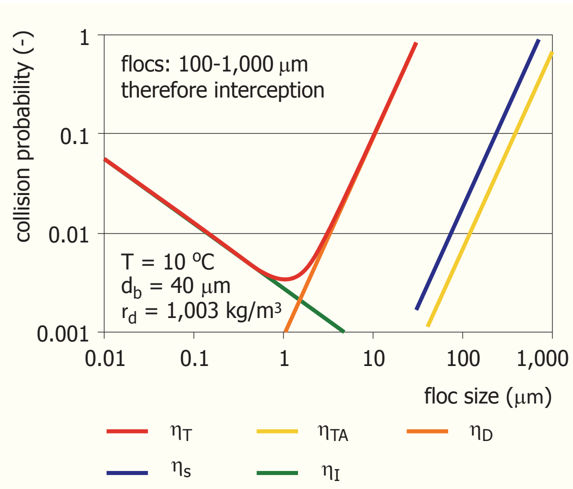


Figure 9 - Collision probability

d_d	=	diameter of the flocs	(m)
ρ_w	=	density of water	(kg/m³)
ρ_d	=	density of flocs	(kg/m³)

The total collision probability η_T is equal to the sum of the separate collision probabilities of each transport mechanism:

$$\eta_T = \eta_D + \eta_I + \eta_S + \eta_{TA}$$

In Figure 9 the collision probabilities are represented as a function of the floc diameter, and the following can therefore be concluded:

- the diffusion mechanism is predominant for flocs smaller than 1 μm
- the interception mechanism is predominant for flocs larger than 5 μm.

From the equation of collision probability for interception and Figure 9, it can be concluded that with an air bubble of 40 μm diameter, the collision probability η_T =1, if the floc diameter is larger than 32 μm. After this manner of floc formation, the floc size is between 100 and 1,000 μm.
Consequently, in practice, the interception mechanism predominates and the collision probability is equal to 1.

The progress of the total collision probability in Figure 9 is equivalent to the curves of the collision probability in the filtration and the floc formation theories.
Similar to filtration, the collision probability is minimal for particle sizes of about 1 μm.
The main difference between the processes, however, is that the collision probability in flotation processes is an order of magnitude larger than in filtration and, therefore, the flocs will collide more easily during flotation.

3.4 Determination of the surface loading of the separation zone

Removal of air bubble-floc aggregates takes place in the separation zone.
All aggregates are removed if the time needed for the flotation of an aggregate at the bottom of the

separation zone is less than the residence time in the separation zone (the opposite of discrete settling):

$$\frac{t_b}{t_{st}} > 1$$

in which:
t_b = residence time in the separation zone (s)
t_{st} = time an aggregate needs to reach the water surface (s)

Assuming a plug flow in the separation zone:

$$v_{st} > v_{so} \cdot \frac{1}{1-m}$$

in which:
v_{st} = rising velocity of the air bubble-floc aggregate (m/s)
v_{so} = surface loading in the separation zone ($m^3/(m^2 \cdot s)$)
m = fraction of dead space (eddies) in the separation zone (-)

It can be concluded that the maximum surface loading is determined by the rising velocity of the aggregates in the separation zone.

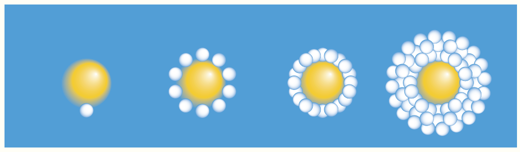
Rising velocity of the air bubble-floc aggregates
Assuming a laminar flow and spherical aggregates, the rising velocity can be calculated with Stokes' Law:

$$v_{st} = \frac{1}{18} \cdot \frac{g}{\nu} \cdot \left(\frac{\rho_w - \rho_a}{\rho_w} \right) \cdot d_a^{\,2}$$

in which:
ρ_a = density of the aggregate (kg/m^3)
d_a = diameter of the aggregate (m)

The density and the diameter of the aggregate can be determined with the following equation:

diameter of air bubbles = 40 mm
diameter of floc = 200 mm



b	0.008	0.08	0.8	8.0
$\frac{d_a}{d_d}$	1.00	1.03	1.21	2.08
ra	995.1	928.8	557.8	112.5 kg/m^3
v_{st}	0.43	6	44.7	152 m/s

Figure 10 - Air bubble-floc aggregate parameters

$$\rho_a = \left(\frac{\beta}{\beta+1} \right) \cdot \rho_b + \left(\frac{1}{\beta+1} \right) \cdot \rho_d$$

$$d_a = \sqrt[3]{1+\beta} \cdot d_d$$

in which:
β = volume ratio between air bubbles and flocs in the aggregate (-)

In Figure 10 the influence of the volume ratio on the diameter, density and rising velocity of the aggregate is represented.

In calculating the diameter of the aggregate d_a, the volume of the air bubbles is assumed to be divided over the entire surface of the floc. It is practically physically impossible for more than one bubble layer to exist. For a floc diameter of 200 μm, this results in a maximum volume ratio of 1.
The volume ratio between the total volumes of inserted air and flocs is about 500. Thus, only 0.2% of the total inserted air is effectively used during the floc removal process.

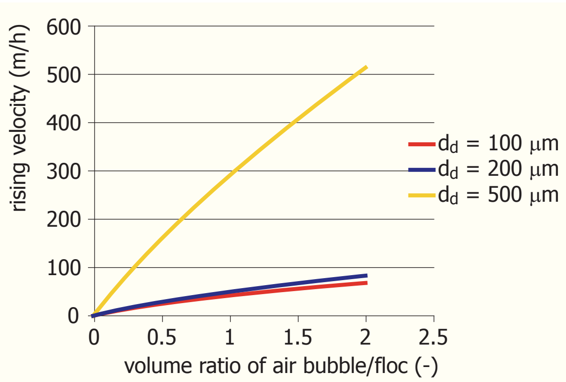


Figure 11 - Rising velocity for different β

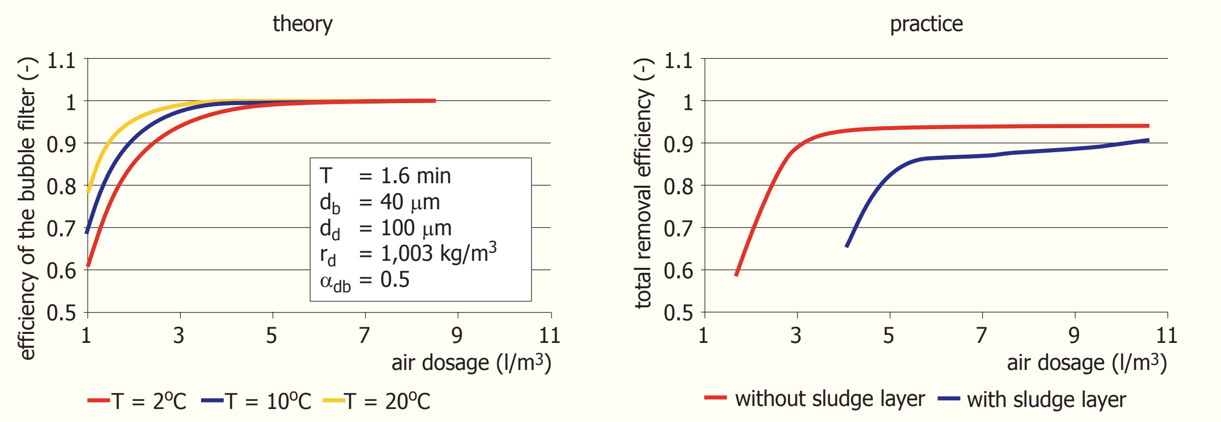


Figure 12 - Influence of air dosage in theory and practice (total efficiency)

The applied (high) air dosage, however, is necessary for a sufficiently high efficiency of the bubble filter in the filtration zone.

In Figure 11 the rising velocity is represented as a function of volume ratio for flocs with a diameter of 100 μm, 200 μm and 500 μm.
Because the volume ratio between air bubbles and flocs is (physically) restricted (β_{max} » 1), an increase in the rising velocity v_{st} can only be realized by an increase in floc size.

4 Practice

4.1 Process parameters

Air dosage

The relationship between air dosage and efficiency of the bubble filter is exponential, as seen in Figure 12.

In addition it can be concluded that at lower water temperatures, higher air dosages are required to obtain the same efficiency.
The air dosage is an operation parameter for the efficiency of the bubble filter.

In Figure 12 the total removal efficiency, measured in practice, is represented as a function of the air dosage. The total efficiency consists of the efficiency in the filtration zone and the efficiency in the separation zone.
The total efficiency approaches the value 0.9 – 0.95 and not 1.
This can be due to the occurrence of short-circuit flows in the filtration zone, resulting in a decrease in the efficiency in the filtration zone or to the limited influence of the air dosage on the efficiency in the separation zone (less than 1% of the air is effectively used for separation), and separation in practice is not optimal.

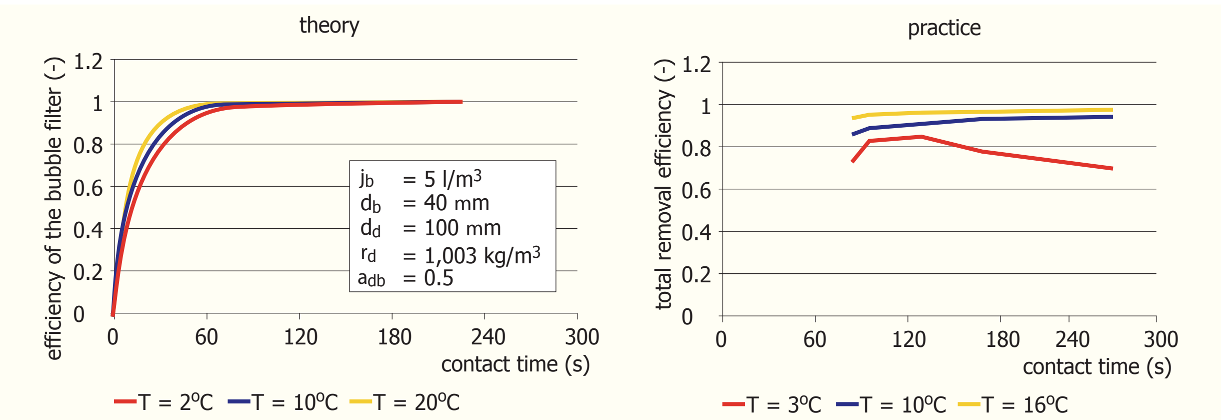


Figure 13 - Influence of contact time in theory and practice (total efficiency)

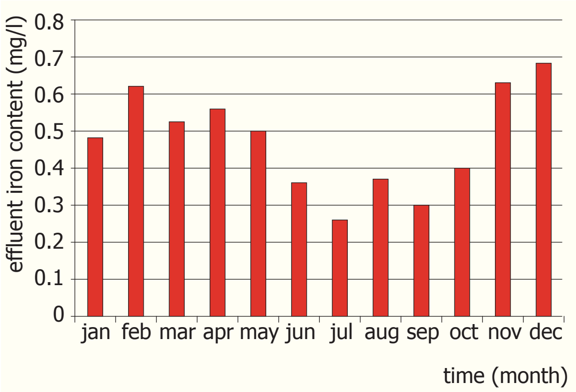


Figure 14 - Seasonal influence by temperature variation

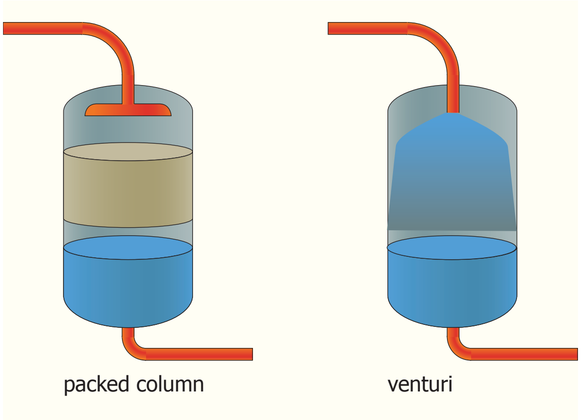


Figure 15 - Saturation units

Contact time

Theoretically, the contact time should be longer than 90 seconds, as seen in Figure 13.
In practice, contact times of 54 to 126 seconds are applied.

In this figure, the results of measurements on full-scale plants, where the contact times are varied, are represented.
In general, the theory is confirmed, but an efficiency of 1 is not reached, even with infinite contact times.
The reason is that in cases where the contact times are increased, the water flow must be decreased (for the same flotation tank). At low water flows, plug flow no longer occurs and the efficiency will be lower than 1.

Temperature

The water temperature determines the viscosity of the water, influencing both filtration and separation.
From calculations it can be derived that the air dosage at 5 °C must be a factor 1.6 to 1.7 higher than at 20 °C to obtain the same efficiency (Figure 12).

It can also be derived that the rising velocity of an aggregate in the separation zone is 1.6 times lower at 2 °C than at 20 °C.
Therefore, the efficiency in the separation zone will be lower at lower temperatures.
In Figure 14 the progress of the residual iron concentration in a flotation system is represented. The temperature effect is obvious.

4.2 Saturation

Saturation unit

In practice, two types of saturation units are applied.
The saturation units can be of a packed column type, similar to the tower aerator systems, or of a venturi type, similar to the venturi aeration systems.
The saturation units that make use of a packed column, similar to the tower aerator system, or the venturi aeration units.
Both systems are schematically represented in Figure 15.

For the design and functioning of the saturation units, reference is made to the module on aeration and gas stripping.

Nozzles

In Figure 16 the principle of a nozzle that is applied

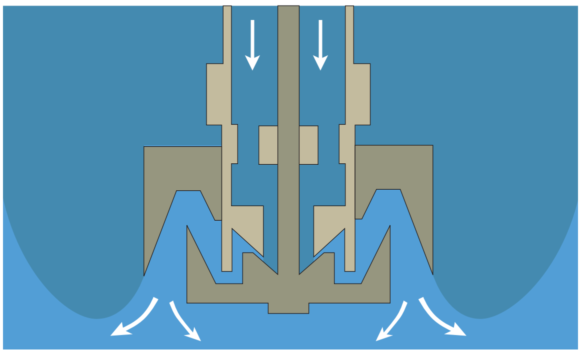


Figure 16 - Nozzle

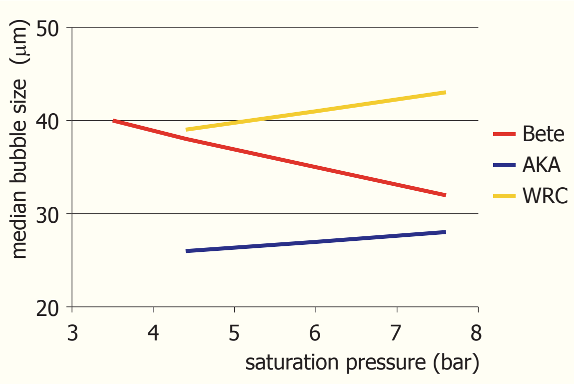


Figure 17 - Performance of three different nozzles

in the filtration zone for the distribution of saturation water is shown.

In practice Bete, AKA and WRC nozzles are applied.
In Figure 17 the median bubble diameter for the different nozzles is given as a function of saturation pressure of the recirculation flow.

Based on the required median bubble diameter, a nozzle and a saturation pressure can be chosen. The median bubble diameter is, for most of the nozzles, between 30 µm and 40 µm.

4.3 Flotation tank

In Figure 18 a flotation tank with a filtration or contact zone, separation zone and baffle is represented. These will be discussed in the following paragraphs.

Filtration zone

The filtration zone (V_c in Figure 18) is designed based on a contact time longer than 90 seconds. To obtain a plug flow in the filtration zone, the length/width ratio must be higher than 5 (long

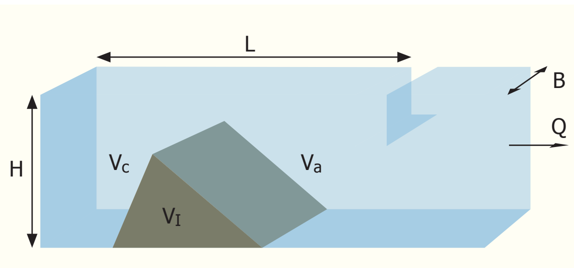


Figure 18 - Design of flotation tank

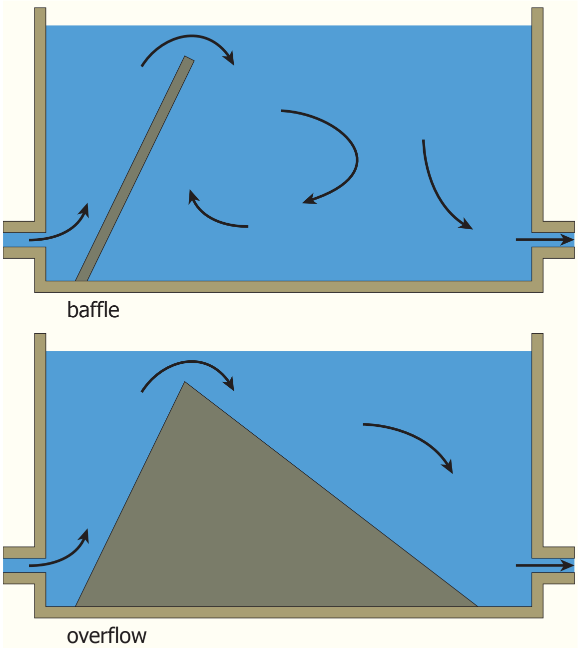


Figure 19 - Division of filtration and separation zone

and narrow).
A column reactor would thus be suitable for the filtration zone.

In existing flotation tanks, the saturation water is released into the filtration zone, resulting in local (near the nozzles) velocity gradients of 20-30 m/s, turbulence and break-up of flocs and bubble-floc aggregates.
Therefore, strong (and thus small) flocs must be formed during floc formation to resist the turbulent flows.

Moreover, this turbulence can be minimized by the arrangement of the nozzles. An example of this is the application of a separate nozzle zone outside the main water flow.

Separation zone

The separation zone (V_a in Figure 18) is designed based on surface loading, which is determined from the rising velocity of the bubble-floc aggregates and takes the dead zones VI into account.
In practice, surface loadings of 10 to 25 $m^3/(m^2 \cdot h)$ are applied.
The residence times in the separation zone vary between 5 and 10 minutes.
The height H must be about 2 meters to avoid

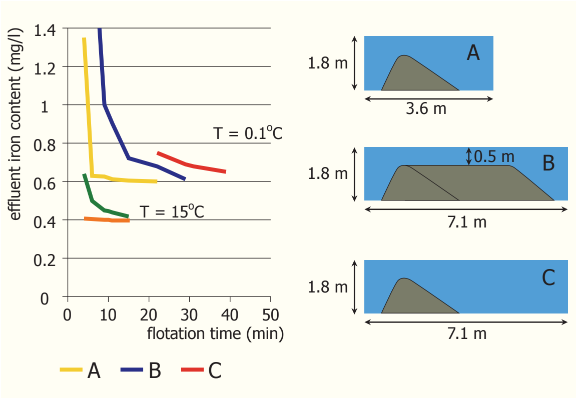


Figure 20 - Design of flotation tank with different overflow structures

large flow gradients and the zone must be long and narrow to approach a plug flow.
Finally, the water flow must be uniformly distributed and collected over the width of the separation zone to limit the fraction of dead zone.

Division between filtration zone and separation zone
The division between the filtration zone and separation zone is achieved with a baffle or an overflow (Figure 19).
Comparing the overflow structure with the baffle, no difference is observed in effluent quality and residence time. In both cases the residence time is about 70 % of the gross residence time (Figure 18):

$$t_{bruto} = \frac{Q}{V_{br}} = \frac{Q}{L \cdot B \cdot H} = \frac{Q}{V_c} + \frac{Q}{V_a} + \frac{Q}{V_l}$$

The flow conditions with an overflow are favorable and less sludge is deposited. It can therefore be concluded that an overflow is preferred above the baffle.

Different types of overflow structures are represented in Figure 20.

Advanced literature

- Flotatie: Theorie en praktijk (Dutch), G.J. Schers MSc thesis TU-Delft (1991)
- Summary: H_2O (in Dutch), 5th Gothenburg Symposium (1992)

Further reading

- J. Haarhof