Development of dissolved air flotation technology from the first generation to the newest (third) one (DAF in turbulent flow conditions)

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Abstract This paper gives a brief description of the development of dissolved air flotation DAF (or so-called high pressure flotation) as an unit operation for removal of solids in water and wastewater treatment during the last 80 years up to this time. The first DAF-systems used in the water industry were the ADKA and Sveen-Pedersen ones from the 1920s. Some of these are still in use. The tanks in which the flotation phenomenon takes place in these systems are very shallow and narrow as well as rather long. The flow rate of water is some 2–3 m/h (at most less than 5 m/h only) and there is a very thin micro-bubble blanket below the water surface between the dry sludge blanket on that and the clarified water which flows almost horizontally below the bubble blanket toward the end of the tanks to be taken out there from near the bottom.

The second generation of DAF was introduced in the 1960s and these units are widely in use today. Their tanks are almost square ones having usually a little bit more length than breadth. They are rather deep, too. There is an under-flow wall in front of the back wall of the units having a narrow horizontal gap on the bottom of the tanks for letting out the clarified water from the flotation space. The flow rate of water is usually 5–7 m/h or at most less than 10 m/h. The direction of flow is 30–45º below the horizontal. There is a rather thick micro-bubble bed at the beginning of the tank below the dry sludge blanket. This bubble-bed becomes clearly thinner, when going toward the end of the tank. There are also round DAF tanks which are based on the same hydraulic principles as the rectangular ones presented above.

A special application of DAF called the flotation filter was invented at the very end of the 1960s. It is a combination of flotation and rapid sand filtration, both of those being placed in the same tank. Flotation takes place in the upper part of the tank and the filter has been placed in the lower part of it. The direction of water flow is now vertically down from the free surface of water in the tank toward the deep-bed filter. This controls the direction of flow in the flotation space of the tank above the filter bed. The flow rate of water in flotation filters may be 10–15 m/h, but the flow conditions are still laminar. It is the threat that the head-loss of filters would grow too rapidly which in practice is limiting the hydraulic flow rate of flotation filters in this area.

The third generation of DAF has been developed at the end of the 1990s. The operational idea is based on that of the flotation filter. The filter bed on the bottom of the tank has been replaced by a thin stiff plate with plenty of round orifices throughout the plate. This plate, having a very much lower flowing resistance than a sand filter can have, controls the vertical flow of water in the flotation space above the plate and distributes it evenly throughout the horizontal cross-section of the tank. The flotation tank is almost square seen from above and its depth is clearly more than the length and breadth of it. This kind of flotation unit can be operated with flow rates of water in the range 25–40 m/l. Even a flow rate of more than 60 m/h has been reported from this kind of DAF-units. There is no risk of clogging of the plate by suspended solids which could limit the flow rate.

This is to say that it is possible to operate DAF also in turbulent flow conditions. The depth of the micro-bubble bed below the surface of water can be 1.5–2.5 m. There actually is a continuously regenerated micro-bubble bed in the tank filtering water which is going through this bed. The lower surface of the micro-bubble bed is really a horizontal one a little bit above the plate controlling the flow in the flotation space. The clarified water below the micro-bubble bed is totally clear. It can be said that in this case the removal of suspended solids takes place much more by filtering water by a deep-bed micro-bubble filter than by attaching micro-bubbles onto solids, when both of these are mixed with each other in the inlet shaft of the flotation unit, because the retention time of water in the inlet shaft is very short indeed.

Keywords Dissolved air flotation; creation of micro-bubbles; control of hydraulics; flow conditions; development of DAF technology
Definition of dissolved air flotation in water and wastewater treatment

Dissolved air flotation (DAF) is a unit operation for removal of suspended solids from water, in which particles are lifted up out of water by a large number of air micro-bubbles attached onto them. These invisible bubbles (diameter less than 100 µm) have normally been created by means of so-called dispersion water or high-pressure (40–70 mwp) water containing a saturated amount of dissolved air. The dispersion water, normally 5–15% of the amount of water to be treated by DAF, is fed into that in front of the flotation space in a DAF tank. There are many different methods used in feeding the dispersion water into water to be treated by DAF as well as in distribution of air micro-bubbles released from the dispersion water into the whole mass of water to be treated by DAF.

Creating air micro-bubbles and mixing those into the water to be treated by DAF may also be carried out by injecting pressurised air into the suction side of a centrifugal pump which is used to lift water into a DAF unit. In this application, the total amount of water to be treated by DAF is pressurised to a clearly lower pressure (30–40 mwp) as the dispersion water is pressurised in the “normal” solution mentioned above. If the amount of air dissolved in the water to be treated by DAF is the same as then, when using a small amount of dispersion water, the energy costs of both systems are almost equal in practice. Systems based on high-pressure dispersion water are mainly used when treating water on a large scale.

When the high pressure of dispersion water or a clearly lower pressure of the total water flow to be treated by DAF containing an excess amount of dissolved air is decreased suddenly to the atmospheric pressure at which water will be treated, this excess air of dispersion water or that of the total amount of water to be treated by DAF, is released from it as gas forming micro-bubbles. It is essential that these micro-bubbles are mixed with the total amount of water to be treated just at the beginning of the DAF-unit. The total amount of air to be dissolved into dispersion water or, in other words, the total amount of dispersion water is dependent on the concentration of suspended solids in the water to be treated by DAF. The normal amount of dispersion water mentioned above is sufficient to remove effectively suspended solids from water up to a concentration of 400–500 mg/l. When the concentration of suspended solids is higher than that, the amount of bubbles must be increased according to the concentration of suspended solids to be removed from the water.

Introduction of DAF technology in water and wastewater treatment

Dissolved air flotation was first applied in the dressing of ores as well as in the process industry at the end of the 19th century. It is used for recovering dressed ores as well as other valuable raw materials from water suspensions for exploitation in industrial activities. The particles which are removed from water by DAF in these applications are of commercial value and the target is to recover them as effectively as possible. The efficiency of DAF in these applications is expressed as the recovery rate of particles (%) from water and the amount of the (g/l or kg/m³) having been recovered. It is of only secondary importance, if some of the wanted particles remain in the water after DAF. In the other words, the quality of water after DAF is not very important in this case.

Dissolved air flotation was introduced into water treatment in the 1920s. The technical role of DAF in water and wastewater treatment is exactly the same as in the dressing of ores and process industry. But instead of recovering particles from water, DAF is used in water and wastewater treatment for purification of water by taking particles away from water as effectively as possible. The efficiency of DAF is then expressed as the reduction rate (%) of particles from water and the concentration of particles (mg/l or g/m³) left in the water after DAF. In this way, the reduction rate of particles or their removal efficiency (in per cent) is of interest in water and wastewater treatment. The major interest is the quality of water after DAF.
Among the first DAF systems used in water and wastewater treatment were the ADKA and Sveen-Pedersen ones. The main feature of these systems is the dimensions of their flotation tanks. Those are rather long, narrow and very shallow ones. Usually there is a vertical inlet shaft in the beginning of the tank which is as broad as the tank itself. Water to be treated by DAF is let onto the bottom of the inlet shaft, in which the dispersion water also is let through a few dispersion nozzles located near the bottom of the shaft. There are turbulent flow conditions in the inlet shaft in which water is flowing upwards to the surface of the water in the flotation tank.

In this way, micro-bubbles having been released into the water close to the bottom of the shaft will be mixed in the shaft rather evenly into water to be treated by DAF. Water with micro-bubbles is then flowing almost horizontally in the flotation space of this kind of DAF system, because it is taken out of the system from the end of the shallow flotation space. There is an underflow wall in front of the long, narrow and shallow rectangular tank and clarified water is taken out near of the bottom of the tank. The flow rate of water in the flotation space is normally 2–3 m$^3$/m$^2$·h (or m/h) and in any case clearly less than 5 m/h. There is only a very thin micro-bubble blanket below the water surface in the flotation tank, because the flow rate is very low and the direction of flow is only a little bit below horizontal. In many cases, there is no micro-bubble blanket at the end of the tank at all. This means that there is quite a large portion of the tank (at the end) which is not in an effective use.

It is clear that there is almost no filtration effect of a micro-bubble blanket for the water to be treated in this kind of DAF system, which can be called the first generation of DAF in water and wastewater treatment. This means that the attachment of micro-bubbles onto solids mainly takes place already in the inlet shaft of tanks. But when operating these systems with proper flow rates mentioned above, quite high removal efficiencies for suspended solids have been achieved, however. There still are some of these kinds of DAF systems in use to clarify process water for the pulp and paper industry. A scheme of the Sveen-Pedersen DAF system is presented in Figure 1.

**Invasion of DAF technology in water and wastewater treatment (1960s and 1970s)**

Dissolved air flotation was widely put into use for water and wastewater treatment during the 1960s and 1970s in the Scandinavian countries. The explanation for this was that dissolved air flotation is an overwhelmingly efficient unit operation for removal of light suspended solids created by coagulation and flocculation of humic substances from water by trivalent metal salts, especially when compared with settling by gravity, if cold waters are treated. For instance in Finland, DAF has almost totally replaced settling as a water clarification operation in surface water treatment since the beginning of the 1970s.

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Figure 1  Sveen-Pedersen DAF system (2–3 m/h)
DAF technology was significantly developed during these decades at first in Sweden and later in Finland. The central role of hydraulics in the implementation of an effective DAF began to be understood step by step. The main process arrangements of DAF were not changed at first, but it was found out that, when higher flow rates of water than 5 m/h were wanted, the geometry of flotation tanks should be changed a lot. The tanks became markedly broader and deeper. Also the length of tanks was decreased markedly. It was understood that a tight uniform micro-bubble bed throughout the whole surface area of the tank was needed, if effective removal of suspended solids was wanted. There are also round flotation tanks having the same hydraulic idea in which the inlet shafts are located in the middle of the tanks.

The direction of flow of water in the flotation space was lowered a lot more from the almost horizontal toward the bottom of the tank by increasing the depth of the flotation space. In these, today conventional, DAF systems, the angle of flow down from the horizontal may be some 30–45º. In this way, the flow rate of water in the flotation space of a DAF tank could easily be increased to 5–7 m/h and even up to 10 m/h at most. This resulted in an evenly tight micro-bubble bed below the water surface throughout a flotation tank. The thickness or depth of this micro-bubble bed may be some 30–50 cm at the beginning of a tank. It decreases linearly along a tank, at the end often being only some 20–10 cm.

It is clear that this micro-bubble bed in the upper part of the flotation space has a clear filtration impact increasing the rate of the attachment of bubbles onto solids, because a major part of water to be treated is forced to flow through the bubble-bed. This kind of application of DAF can be called the second generation or conventional. A typical scheme is shown in Figure 2.

When talking about the development of DAF technology, probably the most important step from the point of view of hydraulics has been the invention of the flotation filter, which took place in the late 1960s in Sweden. The idea for this combination of dissolved air flotation and rapid filtration in the same tank is based on the realization that the hydraulic load bearing capacity of a rapid sand filter is quite the same as that of DAF. Hydraulically this combination is an ideal one, resulting in an exactly vertical flow from the surface of the water in the tank directly downward to the filter bed covering the whole bottom of the flotation space. The whole surface of the filter bed in the flotation space in used for letting the clarified water out from the flotation space.

The flow resistance of the filter bed is so high that it equalizes the flow of water evenly throughout the flotation space, so that the vertical flow rate of water downward is exactly
the same everywhere in the flotation space. This means that there is a rather thick micro-bubble bed in the upper part of the tank having an exactly horizontal lower surface. If the height of the flotation space above the filter bed is big enough, the flow rate of water in DAF as well as that in filtration may be easily 10–15 m/h which, in turn, means that the thickness of the micro-bubble bed is 80–120 cm. There is a clear deep-bed micro-bubble filter in the upper part of the flotation space and water is forced to flow through that micro-bubble filter. The role of this micro-bubble filter in the removal of solids is probably much greater than that of mixing micro-bubbles with water to be treated in the inlet shaft of the tank.

The flow rate of water in a flotation filter might be at least 20–25 m/h, but usually a rather low load-bearing capacity of the normal sand filter for suspended solids is limiting the flow rate, so that it cannot be more than 15 m/h without causing too rapid a growth of the filter head loss. This means that flotation takes place clearly in laminar flow conditions. A scheme of the conventional rectangular flotation filter is presented in Figure 3.

Development of high-rate DAF technology with turbulent flow conditions

It is more than probable that the hydraulic working principle of flotation filters has been exploited, when the third generation of DAF systems was developed during the 1990s. When the target has been to increase the flow rate of DAF units over that which is possible in practice by using flotation filters, it has been only a consequent measure to replace the sand filter by some mechanical structure which is able to control the flow of water in the flotation space as well as the filter can do, but which does not have the clogging problem the filter has.

It has been believed until now that flotation can be operated only in laminar flow conditions. This is to say that the maximum flow rate of water could be at most about 25 m/h in the flotation space of a DAF-system, if it is wanted to control the hydraulics. It is well known that, when the flow rate of water exceeds that level of velocity, the flow conditions will inevitably change from laminar to turbulent. The task has been to solve how to control the flow of water in turbulent flow conditions, so that the flotation phenomenon might take place properly. In other words, the problem is how all of the micro-bubbles could rise surely up to the free surface of water in the flotation space, in which the water to be treated flows down with a high velocity from the surface toward the bottom of that space causing a lot of turbulence in the flotation space.
It is obvious that there are different solutions to try in order to answer this question. Among the simplest is that which has been developed by Mr. Oiva Suutarinen of Rictor Ltd in Finland; only the common principles of that high-rate flotation are presented here.

When the flow rate may be 25–40 m/h or even more, it is clear that the geometry of the flotation tank must be chosen according to this hydraulic requirement. The natural flow direction of water in this case is vertically down from the free surface of water directly to the bottom of the flotation tank. This is why the horizontal cross-section of the flotation space is a square and the inlet shaft is located on one side of the square flotation space. Taking into account the flow rate of water to be treated by DAF means that the depth of the flotation space shall be big enough, because the micro-bubbles will be driven deeper, the higher is the flow rate of water in the space and the smaller are the micro-bubbles.

In this case the diameter of the bubbles is, let us say, 40–70 µm. The depth of the flotation space is 2.5–3.5 m and the depth of the tank is accordingly 3.0–4.0 m. This means that the equal walls of the flotation space are shorter than the height of it. There is a thin stiff horizontal plate between the flotation space and the about 0.5 m high bottom space of the tank. There are round orifices of different size all around the plate. The configuration of the plate with these orifices is the most secret part of this turbulent flotation application which has been protected by Finnish, European and US patents.

The role of this perforated plate is to control the flow of water in the flotation space and to distribute that evenly throughout the horizontal cross-section of that space, despite the turbulent flow conditions there. Having seen this turbulent flotation working in a pilot-unit as well as in a full-scale unit, it seems to be completely clear that dissolved air flotation can be operated in turbulent flow conditions also. The thickness or depth of the micro-bubble bed may be, depending on the flow rate, 1.5–2.5 m. It is also clear that this really deep-bed micro-bubble bed plays the major role both in the attaching of bubbles onto suspended solids and the removal of suspended solids from water.

The lower surface of the micro-bubble bed is completely horizontal which shows that the hydraulics of this turbulent flotation is controlled properly. The clarified water below the micro-bubble bed is very clear showing a very good removal efficiency of solids. The water to be treated by DAF is forced to flow evenly down through this micro-bubble bed which is regenerated continuously. The turbulent flow of water can be seen easily, when looking at a pilot-unit having one transparent wall for observation of the flotation phenomenon.
Further development of DAF technology
When considering the further development of DAF technology, taking into account that it is quite clear that dissolved air flotation can be operated as a controlled unit operation also in turbulent flow conditions, the most interesting question is: how could this clarification method of water treatment be optimised? It seems to be clear that DAF’s removal efficiency for suspended solids will not be reduced, when the hydraulic capacity – i.e. flow rate is increased. From this point of view it can be thought that the tank volume needed for dissolved air flotation could be further decreased by increasing the flow rate of water and the depth of the flotation tank.

From the practical point of view it can be said that the limiting factor is the actual rising velocity of the micro-bubbles in the flotation space which is dependent on the flow rate of water. When this is increased in a constant DAF-unit, there will be at last a situation, when the bubbles have been driven to so deep a level in the unit that they start to escape from the unit with water being let out of it. In this way, the removal efficiency for suspended solids would be reduced rapidly.

The real rising velocity of the micro-bubbles in water flowing down vertically is dependent on their size. There is always some specific size distribution of the micro-bubbles depending on the technical solution used for releasing dissolved air as bubbles or injection of air gas to the water to be treated by DAF. When we have an advanced dispersion equipment in use, the diameter of bubbles is always less than 100 µm. This means that we are using bubbles which are really micro-bubbles. It is often reported that the size distribution of bubbles is 40–70 µm or even 40–60 µm.

In theory, the optimisation of DAF is a compromise between the flow rate of water and the size of micro-bubbles. However in practice, if we decide that the minimum reasonable bubble size is 40–60 µm, it seems to be clear that the maximum flow rate of water will be 30–40 m/h, when we do not want to have extra deep flotation tanks (more than 5 m). In the laboratory conditions, we certainly can construct even deeper flotation units for flow rates of water up to 60 m/h or even higher than that and use smaller bubble size than 40 µm, if those are seen worth of searching.

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