A review of the technological developments of dissolved air flotation

Ian A. Crossley and Matthew T. Valade

ABSTRACT

This paper gives a review of current dissolved air flotation (DAF) technology and its application to the municipal sector, particularly drinking water production and, to a lesser extent, wastewater treatment. An explanation of the DAF process is given and issues arising from the technology are discussed. A history of the development of DAF is provided starting from its roots in Scandinavia, and its application in the UK, South Africa, Australia, Asia, and America. Application areas are discussed, using illustrative case studies, with an emphasis on municipal drinking water and wastewater applications. Recent technological advances in reduction of flocculation hydraulic detention times and new proprietary DAF processes are discussed – for example, CoCoDAFF™, DAFRapide™ and AquaDAF™. The conclusions suggest areas for future development work, mainly in improving energy efficiency in micro-bubble production.

Key words | dissolved air flotation, drinking water, filtration, flocculation, high rate, hydraulic loading

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ACRONYMS

BOD	Biochemical oxygen demand
DAF	dissolved air flotation
DAFF	dissolved air flotation/filtration
HDT	hydraulic detention time
IDI	Infilco-Degremont, Inc.
RO	reverse osmosis
SDI	silt density index
SSJID	South San Joaquin Irrigation District
T&O	taste and odor
UK	United Kingdom
VFD	variable frequency drive
WRc	Water Research Center

INTRODUCTION

Purpose of the paper

Since its development in Scandinavia in the 1960s, dissolved air flotation (DAF) has become a well-established water treatment process, primarily connected with drinking water production and the pulp and paper industry, but other applications such as wastewater treatment have also had success. The benefits of DAF remain as valid as ever; these include compact space requirements, high clarifying performance on raw waters containing color and algae and, compared with floc blanket and solids recirculation clarifiers, DAF is relatively insensitive to water temperature. Plants range in size from small package units of less than 5 Ml/d suitable for villages, to large plants such as that being constructed for New York City, at 1100 Ml/d.

Considerable progress has been made in reducing capital cost items – optimizing flocculation processes ahead of DAF, reducing hydraulic detention time (HDT) by a factor of four from 20 to 5 min, and increasing surface loading from 10 m/h to 40 m/h. Less progress has been made on reducing operating costs related to production of micro-bubbles (pumping and air compressor electricity costs). However, the extensive use of variable frequency drives (VFDs) on DAF recycle pumps has contributed to some improvement.

This paper gives a review of current DAF technology and its application to the municipal sector, particularly drinking water production and, to a lesser extent, wastewater treatment. An explanation of the DAF process and its history are given. Application areas are discussed, along with illustrative case studies. Recent technological advances in reduction of flocculation hydraulic detention times and new proprietary high rate DAF processes are discussed – for example, CoCoDAFF™, DAFRapide™, and AquaDAF™. The conclusions suggest areas for future development work, mainly in improving energy efficiency in micro-bubble production.

How DAF works

Many raw waters, when coagulated, produce floc that is difficult to settle. In particular, waters from reservoirs often contain algae and other natural organic material, such as color, and when coagulated, the floc particles often have near neutral buoyancy. The DAF process attaches micro-bubbles to the floc particles, causing them to float to the surface, and clarified water is drawn from below the flotation zone. Therefore, the DAF process is working with, rather than against (as with sedimentation), the natural tendency of such floc particles to float.

The DAF process is shown schematically in Figure 1. Raw water is mixed with chemicals to adjust the pH of the water (if needed), an aluminum or ferric coagulant is added, coagulant aid polymer is added (if appropriate), and the water is then flocculated in a dedicated two- or three-stage flocculation zone.

The floc size for effective flotation is much smaller than for sedimentation; consequently, the flocculation residence time is shorter (normally in the range 5–15 min). The flocculation volume for flotation is less than one-third that required by conventional or inclined plate sedimentation, reducing the needed "footprint" area by at least a factor of three.

After flocculation, the water is exposed to micro-bubbles that are created by supersaturating a proportion of the clarified or filtered water stream – referred to as DAF recycle – with air in a pressurized vessel, then suddenly releasing the pressure, and injecting the DAF recycle flow in a contact zone prior to the flotation zone.

The micro-bubbles attach to the flocculated particles, which rise to the surface of the tank, and form a dense foam. Periodically, this is removed by skimming or hydraulic flooding. Clarified water is drawn from underneath the bubble zone by collection manifolds or, more simply, by an opening at the end of the tank. The level in the tank is usually controlled by means of a weir on the clarified water outlet. The surface loading of the process varies between 10–40 m/h with a normal rating of 15 m/h. (Loading rates are generally quoted excluding the DAF recycle flow and including the gross area of the DAF zone. In contrast, some manufacturers present loading rates using only a portion of the DAF tank (e.g. only the separation zone) and/or include the DAF recycle flow, making the loading rates appear higher.) Residence time in the flotation tank is of the order of 10–15 min. Outlet turbidities from a flotation clarifier typically range from 0.2–1.5 NTU, with a normal performance of 0.5 NTU.
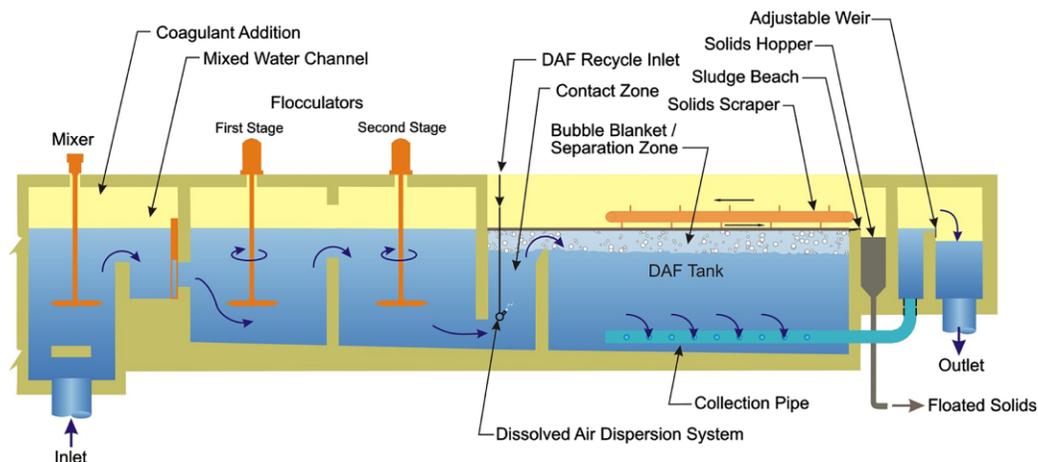

Figure 1 | Typical DAF system schematic.

DAF recycle water can be drawn from the clarified water outlet or from filtered water. Air is driven into solution by either pressurizing the recycle water and passing it through a packed tower, or by mixing air with the water using an eductor followed by a detention vessel to allow the air bubbles to dissolve. Needle valves or fixed orifice nozzles are mounted on manifolds, and it is at this point that the sudden pressure reduction results in the creation of micro-bubbles.

The DAF process has strengths and weaknesses when compared with conventional sedimentation, inclined tube or plate separation, solids recirculation or floc blanket clarifiers.

Advantages of DAF are:

- very compact, low HDTs, high loading rates, small flocculation tanks, leading to lower construction costs;
- low detention time allows rapid start up of $<\frac{1}{2}$h;
- high quality effluent generally <0.5 NTU, leading to longer filter runs;
- good to excellent removal of *Cryptosporidium* and *Giardia*;
- low taste and odor (T&O) impact owing to short detention of algae cells and aeration; and
- solids already concentrated to 3% mass/volume if a skimmer used, leading to less post-processing.

Limitations of DAF include:

- process is not suited to raw waters with high-density suspended solids, for example, a turbid river;
- recycle water requires pumping of up to 10% of the feed flow to between 400–700 kPa, representing a hydraulic power of 0.5–0.8 kW/Ml/d of plant capacity;
- process must be protected from the weather to prevent float freezing leading to settling of previously floated solids caused by snow and rain.

With DAF, the high surface loading rate and low HDT combine to produce a clarification process that is very compact, and the capital (construction and associated equipment) cost is lower than that of conventional sedimentation. The difference in construction cost is smaller when DAF is compared with high rate floc blanket, sand-ballasted or plate settler clarifiers. The lower capital cost of DAF is offset somewhat by the power used to generate the micro-bubbles as that makes the process so effective. On balance, the life-cycle cost of a DAF clarifier is lower than a conventional sedimentation clarifier, especially if there is a shortage of available land for the facility and mechanical dewatering of solids is required. Life-cycle costs of DAF plants with traditional loading rates (i.e. 4–10 m/h) are similar to those of other high rate clarification processes; this is one of the driving forces for the development of high rate DAF processes that are discussed later in this paper.

One of the key building blocks of the DAF process is the recycle system, which is illustrated schematically in Figure 2.
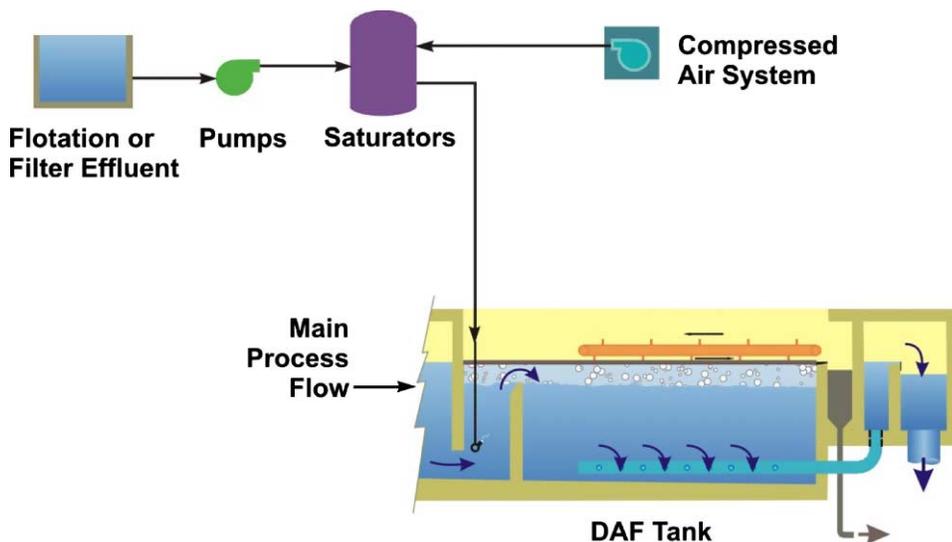

Figure 2 | Typical DAF recycle system.

A DAF recycle system requires taking about a 10% portion of treated water, either floated (i.e. clarified) or filtered water, pumping it through an air saturation system, and controlling the reintroduction of the saturated water back into the main process flow such that micro-bubbles (typical mean sizes of 50–80 μm in diameter) are formed in the contact zone.

The goal of an effective recycle system is to minimize the energy used while maximizing the air content of the recycle flow and the generation of micro-bubbles of the appropriate median size and distribution. Combined with the characteristics of the saturation system, the pressure and flow dictate the amount of air introduced to the main process flow, directly impacting the process performance. An effective and efficient recycle system provides the means to vary the recycle flow rate, maintain saturator pressure to maximize the air content in the recycle water, and properly distribute the recycle flow to the main process flow. Air saturation systems use either packed-tower vessels or eductor systems with a detention vessel, and are normally designed to deliver approximately 9 g of air/m^3 of water treated.

Once the recycle water is saturated, the air must be released to the main process flow to maximize the production of micro-bubbles. The pressure-reducing device (e.g. fixed orifice nozzle or needle valve) is a key component in achieving efficient performance of the DAF process. The rational design of saturation systems and pressure reducing devices was reported by Haarhoff & Rykaart (1995).

Saturated recycle water is normally introduced to the main process flow by means of a series of manifolds located in the contact zone and fitted with either manually adjusted needle valves or fixed orifice nozzles on 150–300 mm intervals to control the rate of flow, pressure drop and formation of micro-bubbles. The injection of the recycle flow from the pressure reducing device should be diffused to minimize floc damage due to excessive shear forces in the contact zone.

The use of manual needle valves or fixed orifice nozzles limits the operation of recycle systems to a relatively small range of recycle flow within the operating pressure band. Fixed nozzle systems require recycle systems to be designed for two or three operating points by means of dedicated manifolds, each fitted with different sized orifices, and being able to switch these manifolds on and off to suit plant flow rate. For example, two manifolds per DAF tank could be provided – one for one-third of the recycle flow, and one for the other two-thirds. By combining the manifolds, a flow through the DAF tank ranging from 33–100% can be accomplished while maintaining the desired recycle flow proportion and pressure in the saturator.

The use of variable frequency drives (VFD) on the recycle pumps widens the economic operating range considerably; however, the micro-bubble size seems to be related to the initial starting pressure, and consequently, typical operating practices involve staying within a pressure band of 400–700 kPa.

Recycle systems are laid out in either dedicated or centralized systems. A dedicated system uses one pump and one saturator to supply one (or two) DAF tanks, while a centralized system has one common set of pumps and saturators that supply multiple flotation tanks. Dedicated systems can provide greater levels of equipment redundancy than centralized systems, although the loss of a dedicated saturation system due to equipment failure (e.g. pump) may impact treatment capacity because the associated DAF tank will be out of service. However, having dedicated systems with more than three DAF tanks will generally add to the plant capital costs and require more maintenance. Consequently, large plants often have centralized recycle pumps and saturators feeding a header common to the bank of DAF tanks.

BRIEF HISTORY OF DAF

Scandinavian roots

The first DAF plant for drinking water treatment was built in Sweden and went on-line about 1965 (Longhurst & Graham 1987). In the following thirty years, over 50 DAF plants were built in Sweden, Finland, and Norway, with the majority located in Finland (Dahlquist 1997). The designs of these treatment plants were typical of early DAF plants, with conservative surface loading rates below 8 m/h and flocculation times, particularly in Finland, as high as 45 min.

In the late 1960s, PURAC AB developed an in-filter DAF process, wherein flotation occurs directly above the filter, thereby reducing the footprint of a treatment plant. This process has become known as dissolved air flotation/filtration (DAFF) and is discussed in more detail below.

UK experience

In 1969, the United Kingdom's (UK) Water Research Center (WRc) undertook a comprehensive research program with the goals of investigating and understanding the fundamental aspects of the DAF process, and how those aspects affect the design and operation of water treatment plants. The investigations included extensive bench- and pilot-scale studies that eventually led to the development of the first widely published findings on the fundamentals of DAF design (Gregory 1997). One of the most significant findings of the initial WRc program of investigations was the determination of the need to sustain backpressure on the saturation recycle flow until injected into the main process flow; this led to the development of a nozzle design that is still widely used today. Other findings of note included:

- establishment of chemical coagulation conditions compared to sedimentation,
- establishing flocculation and DAF loading rate design parameters,
- floated solids removal frequency of scraping/skimming.

The first large-scale DAF plant in the UK was built in the mid-1970s followed by the development of over 90 additional DAF plants over the next 25 years (Schofield 2001), including a very large (550 Ml/d) DAF plant in Birmingham. Since the initial research conducted by the WRc, many of the individual water utilities in the UK have instigated independent research and development programs focused on the optimization of DAF; these have led to a refinement of operational and design parameters including recycle rates, loading rates and new nozzle designs (Franklin *et al.* 1997; Markham *et al.* 1997; Ponton 1997). Typical design parameters for DAF plants in the UK include flocculation times typical for sedimentation, and surface loading rates that were higher than the norm for early Scandinavian DAF plants with rates up to 12 m/h (Table 1).

South African, Asian, and Australian experience

Some of the earliest DAF research was conducted in South Africa in the early 1960s and focused primarily on industrial and wastewater applications. The first DAF plant for water treatment in South Africa went on-line in the early 1960s, using vacuum flotation to treat an algae-laden pond (Longhurst & Graham 1987). Vacuum flotation was developed primarily for application in the mining industry. The first pressure DAF plant in South Africa was constructed in 1969 for the removal of algae from reclaimed sewage

Table 1 | Typical design parameters for drinking water DAF plants

Parameter	Netherlands	Finland Early designs	Finland Recent high rate designs	United Kingdom Early designs	United Kingdom Recent high rate designs	Australia	South Africa	Scandinavia	United States Early designs	United States Recent high rate designs
Flocculation time (min)	8–16	30–45	20	20–29	10	20–24	5–120	26–29	3–30	5–15
Flotation										
Surface overflow rate (m/h)	10–20	3–8	30–40	5–12	20–40	8–12	3–8.2	4–7	6–15	15–40
Percent recycle flow	6–15	5.6–42	10–15	6–10	6–10	5–12	6–23	4–14	8–40	8–15
Saturation pressure (kPa)	400–800	300–700		310–834	400–600	500–550	260–610	470–550	480–700	

Adapted from Edzwald (1995), Haarhoff & van Vuuren (1994) and additional sources cited throughout this article.

(Offringa 1995). Over the following two decades, approximately 26 additional DAF plants were commissioned in South Africa (Schofield 2001). Over the last 10–15 years, researchers in South Africa have continued a strong history of investigation into the fundamental aspects of DAF, with the more recent investigations focused on the principles and design of various components of the recycle system. Haarhoff and others have furthered the understanding of the requirements of nozzle design (Rykaart & Haarhoff 1995) and developed a model that accurately predicts the performance of packed tower saturators (Haarhoff & Rykaart 1995; Haarhoff & Steinbach 1996; Valade et al. 2001) allowing for more efficient full-scale designs to be implemented.

The first water treatment plant to use DAF in Australia was constructed in 1980 (Finlayson 1997). Finlayson (1997) reports that design parameters for Australian plants have tended to be traditional in nature with relatively conservative flocculation times and DAF loading rates (Table 1), although nearly all of the DAF plants in Australia have been designed as DAFF plants. From the time the first plant went on line, at least 26 additional DAF plants have been commissioned in Australia (Schofield 2001). More recently, DAF plants have been constructed in Asia including large treatment plants in Korea (200 Ml/d)), Malaysia (275 Ml/d) and Hong Kong (430 Ml/d).

American experience

The initial experience with DAF in the United States was an adaptation of the European designs by the Krofta Engineering Corporation. The Krofta designs typically had short flocculation detention times (<5 min), surface loading rates of less than 6 m/h and operated with recycle flow ratios as high as 40% (Edzwald et al. 1994). Prior to 1990, five treatment plants were built with the Krofta design, with the earliest one commissioned in 1982.

In 1993, the first treatment plant using DAF for drinking water treatment that followed European design standards using rectangular concrete tanks went on-line at New Castle, NY (Nickols et al. 1995). Because it was the first treatment plant to utilize DAF in the United States, conservative design parameters were used including three flocculation stages, 20-min total flocculation detention times, and DAF loading rates of 6 m/h. (Subsequent to

commissioning of this plant, the authors participated in full-scale testing in order to have the loading rates increased.) Since 1993, DAF has become a widely accepted treatment process in the United States and Canada. Good quality raw water, high construction costs, and land acquisition constraints have led North American engineers to develop aggressive design criteria. Extensive piloting has been conducted by various researchers showing higher loading rates and shorter flocculation times to be feasible (Valade et al. 1996; Shawcross et al. 1997; Nickols et al. 2000). Some of the more recent plants in North America have been designed with surface loading rates of up to 20 m/h and flocculation times as low as 5 min for treatment plant capacities ranging up to 1500 Ml/d. (Nickols & Crossley 1997; Crossley et al. 2001).

More recently, DAF has been investigated as a potential water treatment process in South America. Reali & Marchetto (2000) reported on investigations of DAF for the treatment of colored waters with low turbidity, and Moruzzi et al. (2005) presented findings for a study on the removal by DAF of organic iron from drinking water sources in Brazil. Additionally, a large-scale (75 Ml/d) high-rate DAF plant was commissioned in Manaus, Brazil in 2002.

Table 1 shows various DAF design parameters that are typical for different countries.

OVERVIEW OF MARKETS AND APPLICATION AREAS

Drinking water

As mentioned earlier, DAF is well established in Europe, Australia, South Africa, USA, Canada, and more recently in South America and Asia. It is particularly suitable for treating water from large open reservoirs, particularly where algae can be a problem at certain times of the year. Effective removal of algae makes the process less prone to taste and odor (T&O) problems. The very short residence time of the solids within the clarifier helps limit T&O impacts because the cells do not have time to break down and release their contents. It has also been shown that DAF is more effective than sedimentation in removing protozoa pathogens such as *Giardia lamblia cysts* (Edzwald *et al.* 2000) and

Cryptosporidium parvum oocysts (Edzwald & Kelley 1998; Edzwald *et al.* 2000, 2003). The DAF process has been found to perform much better than sedimentation in very cold waters, such as those found in Scandinavia, the Northeast of the USA, and Canada. Consequently, for impounded sources, DAF is the preferred technology, compared with other clarification processes.

A further advantage of DAF is that it can be "stacked" over gravity granular media filters. This reduces the footprint of the treatment plant dramatically, although it does often limit the DAF loading rate to that of the filtration process and inhibits additional treatment processes between clarification and filtration (e.g. ozone). Normally, granular media filtration loading rates are limited to 10–20 m/h; the DAF loading rate thus tends to be lower because the inlet contact zone takes up a portion of the area of a DAF tank. Even so, stacking the DAF and filtration processes, so-called DAFF or DAF/F, results in an economic configuration.

DAFF is the configuration being used for the 1100 Ml/d capacity Croton Water Treatment Plant (WTP) currently under construction for New York City, USA. This facility is underground, since it is located in a golf course that is part of Van Cortlandt Park, in the Bronx (a borough of NYC). A golf driving range will be located on top of the plant and a new clubhouse is part of the facility. The plant will be in service by 2010. The Croton WTP consists of 48 DAFF units, each rated at 12.2 m/h, with a total flocculation detention time of 4.8 min in two stages. Vertically oriented turbine hydrofoil flocculators are used with each producing up to $100\,s^{-1}$ energy gradient. Floated solids (float) are removed by star-wheel surface skimmers with low-pressure spray bars, to provide a lubricating film between the sidewalls and the float during the removal operation. The granular media filter underneath the DAF separation zone consists of 0.6 m of anthracite and 0.3 m of silica sand media, operating at up to 16 m/h. Filtered water is passed to twenty UV disinfection units rated to give at least 2-log inactivation of *Cryptosporidium*. DAF floated solids will be pumped a distance of about 13 km to NYC's Hunts Point Water Pollution Control Plant for consolidation with the waste from that facility.

A 150 Ml/d high-rate DAF and immersed membrane water treatment plant has been constructed for the South San Joaquin Irrigation District (SSJID) of California and began operation in mid-2005. The DAF plant uses the AquaDAF™ technology described later as pretreatment for Zenon ZW1000 immersed hollow fiber membranes. Ferric chloride is used as the coagulant and coagulant polymer dosing is not used so as to avoid membrane fouling. The DAF loading rate is 35 m/h.

Wastewater – tertiary and thickening

The use of DAF for treating sewage effluent has been limited, perhaps because tertiary filtration using granular media is more popular and produces a better quality effluent. Nevertheless, DAF is a feasible process for this application; one of the largest DAF plants in the world is located at Malmo, Sweden, and has been in operation since 1982 (Crossley & Nickols 1995) The treatment plant is designed for a maximum flow of 380 Ml/d and BOD loading of 40,000 kg/d, but normally operates at an average flow of 150 Ml/d. The treatment plant has two process streams – one based on trickling filters and the other on activated sludge, both feeding secondary sedimentation tanks. Both streams are preceded by screening, grit removal, coagulation with ferrous sulfate and primary sedimentation.

The DAF facility within the wastewater treatment plant has two streams, each with eight flocculation and DAF tanks. The trickling filter stream is treated with a cationic polymer and polyaluminum chloride coagulant. The activated sludge stream is not chemically treated. These DAF tanks, fed from one end, are among the largest in the world, at 16.8 m long and 7.4 m wide. Sludge is skimmed off the top with a chain and flight scraper and transferred by screw augers to paired common storage tanks. A scraper is used to remove solids that settle on the floor of the DAF tanks. On both streams, the DAF process removes suspended solids from 20 to 10 mg/l and BOD from 40 mg/l to 15 mg/l, and on the trickling filter stream, phosphorus is reduced to less than 0.5 mg/l. The layout of the flocculation tanks is of particular interest because the DAF recycle is injected into six ducts that connect the two zones below a lateral access tunnel. This arrangement allows the use of six globe valves to control the recycle flow of up to 15% continuously in proportion with the plant flow, avoiding the need for multiple manifolds fitted with fixed orifice nozzles. The saturators are the type that rely on detention time within the vessel to allow air to dissolve and are fitted with external

air/water eductors. This avoids concerns over fouling of packing material if a packed tower design were used.

Sewage and industrial waste sludge thickening by DAF is used, mainly on primary and secondary waste, as pretreatment for dewatering processes such as belt presses or centrifuges. Loading rates are usually specified by mass flow per area rather than volumetrically. For example, $2–5\,kg/m^2/h$ would be commonly applied if no polymer is used. Discharge sludge concentrations are usually up to 5% and solids capture is usually in excess of 85% (US Filter/Envirex undated). DAF recycle rates for thickening tend to be higher than clarification, usually in excess of 20%. Bottom scrapers and heavy-duty sludge handling equipment are needed. Compared to a conventional sedimentation thickener, a DAF installation will occupy an area approximately ten times smaller.

Filter backwash waste recovery

Depending upon the overall treatment process, granular media filters can generate up to 5% of the incoming flow as wastewater. Many plants dispose of this waste to lagoons and recycle the supernatant. However, such lagoons consume considerable space and can present nuisances, such as odor, to neighboring communities. Filter backwash waste is generated over a short period of about 10 min from a filter that may have been in service for 24–72 h, and consequently, some form of equalization is needed, usually by providing waste tanks sized to hold the volume of two consecutive backwashes. The waste backwash water, usually after treatment, can be recycled to the head of the plant at steady flow rate ($<10\%$ of plant flow and upstream of pre-treatment chemical mixing).Treatment of backwash wastes was comprehensively reviewed and reported upon by Cornwell *et al.* (2000) and Cornwell & McPhee (2001).

Backwash wastewater treatment DAF plants with capacities of up to 6 Ml/d have been installed in Boulder, CO and Municipal Authority of Westmoreland County, PA (Grubbs & Arnold 1997). Several pilot tests have been carried out for Durham, NC; Phoenix, AZ; and Cleveland, OH (Eades *et al.* 2001). Loading and recycle rates for treating backwash wastewater are similar to those normally used for drinking water applications, and treated water qualities indicate $>90\%$ removal of solids and turbidities of around 1 NTU.

Seawater pretreatment for desalination

An interesting application of DAFF is the 136 Ml/d Tuas Water Desalination Plant, in Singapore, which was completed and started up in late 2005 (Kiang *et al.* 2005). The pretreatment for the reverse osmosis (RO) desalination consists of a screened intake sized for 354 Ml/d (approximately 40% recovery), bar screens (30 mm), traveling band screens (3 mm), pumps, pH adjustment to 6.5 using sulfuric acid, and coagulation with ferric chloride. There is a total of twenty in-filter DAF or DAFF units that are used as pretreatment prior to cartridge filters and seawater RO membrane treatment. Flocculation time is reported (Huijbregsen *et al.* 2005) to be 15 min, and filter loading rates of 8 m/h indicate that the DAF loading rates will be of the order of 6.5 m/h, when allowing for 10% recycle with filtered water and a larger DAF than filtration surface area. Redundancy allows for up to two units to be taken out of service for filter backwashing and maintenance. Removable covers are provided over the units to prevent disturbance to the float by wind and rain. Each of the DAFF units is provided with two mechanical flocculators. The water quality at the outlet of the DAFF units has to be oil-free and have a silt density index (SDI) of 3 or less to reduce the fouling potential of the downstream RO membranes. (SDI is a measure of how likely the water is to foul an RO membrane; values less than 5 indicate a low rate of fouling.) DAFF was selected over other pretreatment methods because it offered a smaller footprint, process advantages for removal of bio-fouling material, proven experience from the Paiton Power Station in Java, Indonesia, and economic benefits (Huijbregsen *et al.* 2005).

RECENT TECHNOLOGICAL ADVANCES OF DAF

Based on the findings of investigations by WRc and others in the 1970s on the fundamental parameters affecting the design and performance of DAF, researchers began focusing attention on optimizing performance and pushing the operational envelope. This section reports on the principal advances that have been made that affect the design of DAF treatment plants including the shortened flocculation times and increased surface loading rates.

Flocculation requirements

Edzwald *et al.* (1990) and Haarhoff & Edzwald (2001) presented mathematical models for understanding the bubble–particle interactions of DAF. The earlier model is based on similar principles as models for deep bed filtration and focuses on the particle removal efficiency in the contact zone of a DAF tank. This model identifies key parameters to DAF as being bubble size and concentration, particle size and number, and the adhesion efficiency between the particles and bubbles. Others have shown that the optimum bubble size for effective flotation in DAF should be less than 150 μm in diameter and that the size of the bubble is not easily adjusted during full-scale applications (Rykaart & Haarhoff 1995). The number of particles is primarily a function of raw water quality and coagulation chemistry, as is the adhesion efficiency between particles and bubbles. Therefore, Edzwald *et al.* theorized that for DAF to be most efficient, the treatment chemistry to optimize the bubble–particle adhesion should be similar to that for optimum deep bed filtration, and the particles need to be strong, "pinpoint" floc. Edzwald *et al.* further hypothesized that flocculation design parameters that had historically been used for DAF treatment were overly conservative, since they were based on developing floc particles for sedimentation – long detention times with gentle mixing that allow a large floc particle to develop.

Based on this theory, Edzwald and others showed, initially through bench-scale studies, that flocculation times as low as 5 min upstream of DAF could produce good flotation performance, as long as good chemical pre-treatment is performed (Edzwald & Wingler 1990). Subsequent bench- and pilot-scale studies proved that flocculation times as low as 5 min could be used as part of an integrated DAF treatment plant design (Bunker *et al.* 1995; Valade *et al.* 1996). These investigations further confirm results reported by Janssens (1991), wherein pilot- and full-scale testing of flocculation times of approximately 5 min produce floc that is effectively removed through DAF. These researchers report that careful consideration is required to ensure that the configuration and geometry of the flocculation tanks minimize short-circuiting.

This research has allowed reduced flocculation times to be implemented into full-scale designs, thereby reducing the footprint of a DAF plant without affecting finished water quality. Such a reduction in footprint can have significant capital cost savings for large-scale treatment plants. For example, the 1110 Ml/d Croton DAF plant for the City of New York was designed for flocculation times as short as 5 min.
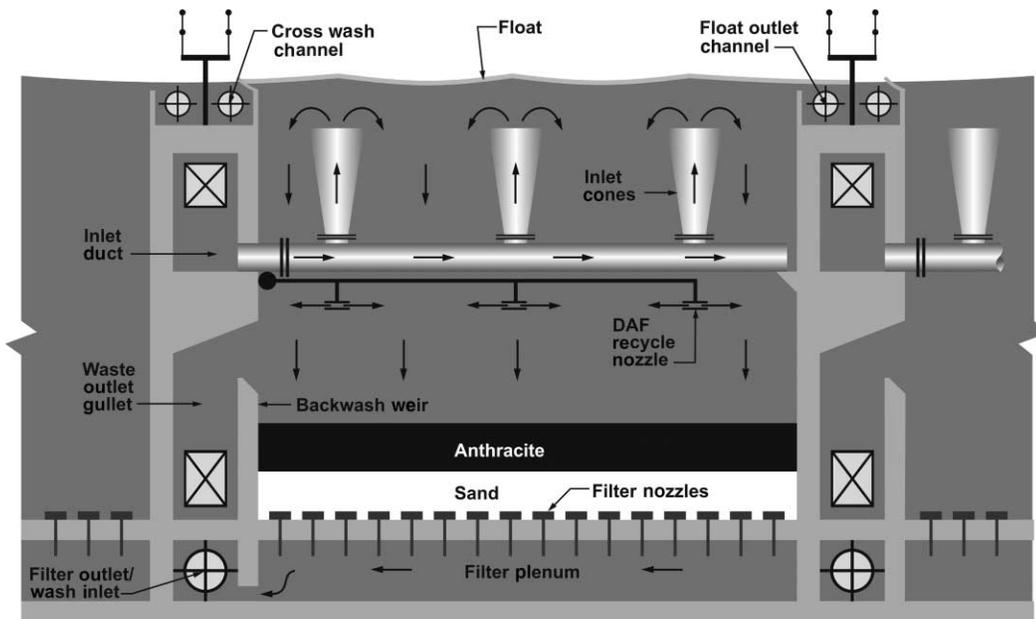
CoCoDAFF™

In the early 1990s, a novel DAF technology was developed in the UK by Thames Water PLC and PWT Projects Ltd. to increase the particle–bubble interaction times by re-engineering the hydraulics of the DAF process to have the flocculated water pass through a greater volume of bubbles (Eades & Brignall 1995; Eades *et al.* 1997). Counter-current dissolved air flotation filtration (CoCoDAFF™) introduces the recycle flow above the filter media through special high volume flow rate nozzles that are designed to widely disperse the bubbles and thereby reduce the number of nozzles needed. Figure 3 shows the typical arrangement of a CoCoDAFF™ tank.

The primary advantages of the CoCoDAFF™ process are:

- improved particle–bubble interactions to increase the flotation efficiency;
- enhanced support of the floc blanket through continuous, evenly distributed introduction of the bubble blanket;
- reduced capital costs from locating the flotation within the filter (although they would be similar to co-current DAFF); and
- reduced operational costs, achieved by turning off the DAFF process during normal raw water conditions and allowing the plant to operate in a direct filtration mode.

Eades *et al.* (1997) reported that pilot testing of CoCoDAFF™ led to the development of design flocculation times of 15 min, surface loading rates of 10–15 m/h, and recycle ratios of 10%. Loading rates on the DAF zone are effectively limited by the filter loading rates, which tend to be less than those feasible by DAF alone, plus the DAF recycle is added to the filter loading rate while it is not normally considered part of the DAF loading rate. The 140 Ml/d Walton Advanced Water Treatment Works in London was the first full-scale CoCoDAFF™ plant constructed and went on-line in 1995. Since then, seven additional CoCoDAFF™ plants have been placed in service, including a 400 Ml/d plant in Portugal and a 240 Ml/d plant in Wales.

CoCo DAFF™ cross section schematic

Figure 3 | Typical CoCoDAFF℠ arrangement (Courtesy of Black and Veatch).

High rate DAF

In the last few years, high rate DAF processes that offer the advantage of reducing the footprint of DAF plants have become commercially available. These advanced processes have built upon the fundamental aspects of DAF and push the envelope of operating parameters by incorporating proprietary elements to the design.

DAFRapide℠

DAFRapide℠ was developed by Purac Ltd. and Purac AB and incorporates an integrated approach to treatment plant design. Combining reduced flocculation times with flotation loading rates of up to 40 m/h allows for compact designs and capital cost savings. As reported by Amato *et al.* (2001), the DAFRapide℠ flotation process was developed to minimize the carry-over of bubbles from the flotation zone at high loading rates. Although bubbles do not carry over a significant amount of particles, filter run times can be reduced if the bubbles enter and collect in the filter media (Valade *et al.* 1996). Edzwald *et al.* (1999) investigated methods of air removal to limit bubble carry-over, and showed that the majority of bubbles that carry over from the DAF tank will rise to the

surface prior to reaching the filter media. DAFRapide℠ technology was developed based on this research, and incorporates inclined plates and a distribution mechanism in the lower region of the DAF cell to inhibit bubbles from being carried over to the filters (Figure 4).

Pilot testing conducted by Edzwald and others (Edzwald *et al.* 1999; Amato *et al.* 2001) confirmed that DAF loading rates of up to 40 m/h are attainable with a properly configured DAFRapide℠ system. DAFRapide℠ has been successfully installed on full-scale facilities with capacities up to 120 Ml/d.

AquaDAF℠

Originally developed by Rictor AB in Finland and licensed by Infilco-Degremont, Inc. (IDI), AquaDAF℠ is reported to achieve surface loading rates up to 40 m/h (Suutarinen 2000) with potentially higher loading rates. It is worth noting that IDI (and other manufacturers) includes only the DAF separation zone area in calculating loading rates. This latter method results in higher loading rates than if they are calculated based on the gross footprint area of area of the DAF tank. Similar to DAFRapide℠, the AquaDAF℠ process utilizes a

Figure 4 │ DAFRapide™ unit (photo courtesy of Purac AB).

Figure 5 │ Typical AquaDAF™ tank configuration (courtesy of IDI).

proprietary distribution mechanism in the lower region of the DAF tank (Figure 5) to inhibit bubble carry-over to the filters. Prior to the licensing agreement with IDI in 2001, Rictor had installed this technology in over 30 drinking water treatment plants, with a majority of them located in Finland. Since the licensing agreement, IDI has about a dozen treatment plants in operation or under construction throughout the world, including a 290 Ml/d

plant in Brazil, an 80 Ml/d plant in New York, and the SSJID 150 Ml/d plant in California referred above.

CONCLUSIONS

Over the past thirty years, the advancements in the understanding of the DAF process have been significant and include:

- a better understanding of what raw waters are suitable for DAF treatment,
- the importance of optimal coagulation for the proper operation of DAF facilities,
- a large reduction in flocculation detention times – as low as 5 min,
- increased DAF loading rates – as high as 35–40 m/h.

This improved understanding of DAF operation and large increases in hydraulic loading rates (sometimes due to proprietary processes) have allowed DAF plants to have significantly smaller footprints, thereby drastically reducing capital costs.

The primary factors influencing the principal operating cost of a DAF plant remain unchanged over the last 40 years. Although further advancements related to reduction in plant footprint may be possible, the added capital costs savings will be minimal, while the operating costs of DAF plants have not been significantly impacted by the advancements to date. Recycle ratios and pressures required for saturation and bubble formation have not been significantly modified from those established in the original WRc investigations in 1969. In order to push the envelope further and continue to reduce the cost of implementing DAF, additional investigations are required to optimizing the recycle systems design or finding new, novel methods for forming micro-bubbles with the proper characteristics for flotation.

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