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Dissolved air flotation: progress and prospects for drinking water treatment

Johannes Haarhoff

ABSTRACT

The development of dissolved air flotation (DAF) for drinking water treatment has come a long way. After its pioneering application to water treatment in the 1920s, it was seemingly forgotten until renewed interest in the 1960s in Sweden, Finland, southern Africa and the United Kingdom brought it to attention once more. These advances converged at the first DAF conference in 1976 to unify the international DAF agenda. Subsequent meetings in 1991 (Antwerp), 1994 (Orlando), 1997 (London) and 2000 (Helsinki) provided important milestones for benchmarking the evolution and acceptance of DAF as a viable drinking water treatment process. The versatility of the process spawned a wide range of innovations to increase its efficiency, to optimise its energy use, to reduce its footprint and capital cost, to integrate it with filtration, sedimentation and ozonation, and more recently to use it in conjunction with membrane treatment. Although DAF innovation continues unabated, for example to improve hydraulic flow patterns and to produce bubble suspensions with more precise size and charge distribution, the process has now clearly crossed the chasm between the experimental (the "early adopters" phase) and maturity (the "early majority" phase).

Key words | bubble production, dissolved air flotation, loading rate, technology development

Johannes Haarhoff
Department of Civil Engineering Science,
University of Johannesburg,
Kingsway Campus, PO Box 524,
Auckland Park, 2006,
South Africa
Tel.: +2711 559 2148
Fax: +2711 559 2395
E-mail: *jhaarhoff@uj.ac.za*

INTRODUCTION

Dissolved air flotation (DAF) is a relatively new unit process for drinking water treatment. The first international conference, as an example, was only convened in 1976 and the presentations and discussions from that conference portray a clear picture of experimentation, empiricism and some hesitancy as critical design parameters were proposed and challenged. Research and development have continued unabated during the intervening 30 years. It is the objective of this paper to trace the technological development of the DAF process to the present day and to assess the degree to which the world of drinking water treatment has embraced DAF as a viable, robust option alongside other, older unit processes.

DAF FOR DRINKING WATER TREATMENT

The first reported use of DAF for drinking water treatment was the introduction of the ADKA system (a vacuum flotation system) in Scandinavia during the 1920s, with at least two of these plants still operating in Sweden in the 1970s (Rosen *et al.* 2008). These systems were characterised by long, shallow tanks with low (less than 5 m/h) hydraulic loading. It is not reported how many of these systems were built, but they apparently fell out of favour for drinking water treatment, although some were still used in the paper and pulp industry as late as the end of the 20th century (Kiuru 2001). During the 1960s, DAF technology was re-examined in Sweden, and shortly thereafter in Finland, to give a renewed thrust to the introduction of DAF to drinking water treatment. By making the separation zone deeper and broader, the hydraulic loading could be increased to between 5 and 10 m/h. These re-engineered DAF systems were first introduced in Finland in 1965 and have almost totally replaced settling since the beginning of the 1970s (Heinänen *et al.* 1995; Kiuru 2001).

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Parallel and independent to these developments, the early 1960s saw extensive studies in Namibia and South Africa in preparation for the direct wastewater reclamation system that was commissioned in Windhoek during 1968, using algal-rich water from wastewater maturation ponds as a raw water source. While performing laboratory jar tests in 1964, it was observed that high turbulence (induced by simply pouring the water into a measuring cylinder) caused algae to float spontaneously due to the release of small oxygen bubbles due to photosynthesis. This autoflotation phenomenon was first exploited at pilot scale (Van Vuuren & Van Duuren 1965; Van Vuuren *et al.* 1965, 1967) and subsequently at full scale (Van Vuuren *et al.* 1970). This work was broadened to other applications and more sophisticated aeration methods such as, for example, a DAF plant with full-stream pressurisation to treat sewage effluent for paper processing (Van Vuuren *et al.* 1972). Further South African advances followed from the fundamental work done at the University of Cape Town on the thickening of activated sludge with DAF, resulting in an influential series of publications (Bratby & Marais 1975*a*,*b*, 1976).

During 1969, Ron Packham of the Water Research Centre (WRc) in England visited the Windhoek wastewater reclamation project. Here he witnessed the full-scale flotation of algae and was undoubtedly also informed about other DAF developments in South Africa. This was the origin of the WRc's own comprehensive, systematic investigation into the use of DAF for potable water treatment (Gregory 1997). At first, the objective was to demonstrate its cost efficiency in comparison with sedimentation, with the emphasis later shifting towards DAF optimisation and its effects on the subsequent filtration step. The outcomes of this programme had been succinctly summarised by Gregory (1997).

DAF AT INTERNATIONAL PLATFORMS

The developments of the 1960s and early 1970s stimulated an academic interest in flotation. Early contributions considered bubble behaviour in dilute suspensions (Zieminski *et al.* 1967), the effect of bubble size on separation (Cassell *et al.* 1974) and the interaction between bubbles and flocs (Reay & Radcliffe 1973). Furthermore, by the middle of the 1970s, a number of full-scale and pilot-scale applications had been ongoing or completed in different parts of the world. All these developments paved the way for the ground-breaking conference held during June 1976 in Felixstowe in England, organised by the WRc. At this conference, despite only 13 papers being presented, the international DAF community shared a common platform and discussion forum for the first time with speakers from Sweden, France, the USA, the Netherlands and England. Among the 270 delegates, 80 were from countries other than the United Kingdom (Gregory 1997). The four sessions at the conference were devoted to sludge thickening, industrial treatment, potable water treatment (mostly the WRc's own studies) and practical experience with commercial DAF plants (with speakers from Sweden, the UK and the Netherlands). The Felixstowe conference can thus be regarded as the start of international DAF collaboration and undoubtedly stimulated the interest in DAF. The international collaboration continued at a workshop in Antwerp in 1991, attended by a small group. Seven invited speakers from Belgium, France, Germany, the Netherlands, Scandinavia, the UK and the USA could report on the significant progress that DAF had made in their respective countries.

The second conference was held in Orlando, Florida, during April 1994, 18 years after Felixstowe. The breadth and depth of the papers read at the important Orlando conference provided clear evidence that DAF had gathered a critical mass of researchers and practitioners. A record 28 papers were presented from 10 different countries, of which a large number were subsequently published as peer-reviewed papers in *Water Science and Technology*. Orlando had set the standard for the following conferences–London in 1997 (36 papers from 12 countries with a hard-bound book of the proceedings), Helsinki in 2000 (58 papers and posters from 16 countries) and Seoul in 2007 (41 papers and 12 posters from 13 countries).

AIR SATURATION AND BUBBLE PRODUCTION

The production of sufficient air is the first DAF prerequisite. Early studies thus focused on how much air was required to effectively sweep the flocs from suspension, now accepted to be 8–10 mg/l for most applications directed at clarification. In the same period, practical design guidelines for packed saturators in terms of hydraulic loading (about 15 kg m^{-2} s^{-1} or 15 m h^{-1}), packing size (15–45 mm plastic rings), packing depth (about 800 mm) and saturator pressure (400–600 kPa) evolved. Attention then turned to the prediction of the nitrogen-enriched air composition of the air within saturators (Rees *et al.* 1980) and methods to measure the air transfer efficiency (Bratby & Marais 1975*b*; Haarhoff & Steinbach 1997). Eventually, a rational model for saturator design, based on mass transfer fundamentals, could be developed and verified at full scale (Haarhoff & Rykaart 1995; Valade *et al.* 2001). By 1997, the body of knowledge regarding saturators was robust enough, for example, to allow a large utility to systematically evaluate the saturation systems at 15 operational DAF plants, adapting and optimising them where necessary (Franklin *et al.* 1997). For many years, numerous attempts had been made to eliminate the air saturator by direct air injection into the suction side of the recycle pump (the most recent proposal being by Chen *et al.* 2004), an option not widely accepted at present. The principal problem is to introduce the highest possibile air concentration (to keep the recycle flow as small as possible) without causing the recycle pump to cavitate or drift from its performance curve.

The pressurised water is released in the contact zone with either adjustable needle valves (which offer the attractive option of being self-cleansing when occasionally fully opened) or with non-adjustable micro-nozzles. The 1970s and 1980s saw a proliferation of different nozzles protected by patent, for example the WRc nozzle from England, the Rictor nozzle from Finland, the cupped NIWR nozzle from South Africa and the adjustable DWL nozzle from the Netherlands. A study of these nozzles in the early 1990s showed that these nozzles shared one or more of the following features (Rykaart & Haarhoff 1995):

- the pressure drop occurs within a very small time (about 1.5 ms or less),
- the flow path offers one or more sharp changes in direction,
- the small jets issuing from the nozzle are directed onto an obstructing surface,
- the jets from the nozzles are guided with a gradually outwardly taper section.

(It is appropriate to include an anecdote on how Lucas van Vuuren of the National Institute of Water Research in South Africa stumbled upon the discovery that smaller bubbles are formed when the jets from the nozzle impinge onto a solid surface. He once playfully tried to block the flow from an uncupped nozzle by squeezing his finger over the jet opening while the nozzle was submerged. The pressure of the recirculation pump prevented him from completely stopping the flow, but the bubble suspension instantanteously and visibly changed to a more homogenous, milky suspension. Further investigation eventually led to the widely used "cupped" NIWR injection nozzle (Van Vuuren, personal communication 1993)).

The market is still dominated by proprietary nozzles, which are continuously refined and improved, for example a nozzle designed by Yorkshire Water (Franklin *et al.* 1997), the KERAFLO nozzle, an adapted ball valve used since 1991 in Finland (Takko 2000*b*), the WPFS nozzle (Järvenpää 2000) and a novel pneumatically adjustable nozzle which offers a constant pressure drop independent of recycle rate, used since 1994 in Belgium (Cromphout & Vandenbroucke 2000).

The assessment of saturation systems, and especially injection nozzles, steadily improved over the years as better methods of bubble characterisation became available. Earlier methods used photographic methods coupled with optical image analysis, but easier and quicker alternatives have since been found. They include the use of a particle counter (Han *et al.* 2002*b*); a digital viewing and imaging system which eliminates the problems of poor focus, poor illumination and obscuration (Rodriques & Rubio 2003); and a light attenuation technique for measuring the void fraction in a bubble suspension (Leppinen & Dalziel 2001). Earlier photographic work, for example, could only show that higher saturation pressure (500 kPa versus 200 kPa) led to smaller bubble sizes (Rykaart & Haarhoff 1995), but the particle counter method can show a more detailed response–from 200 to 350 kPa the bubble size did decrease, but there was no further effect on bubble size if the pressure was further raised to 500 kPa (Han *et al.* 2002*a*). A more recent concern is the detrimental effect of macro-bubbles (bubbles of about 150 μm or larger) which are especially evident when needle valves are used as injection nozzles. Not only do the relatively few macro-bubbles deprive the suspension of a large fraction of the dissolved air (Haarhoff 1997), but they also reduce the efficiency of separation (Leppinen & Dalziel 2004).

Air bubbles in water are negatively charged, well known from mineral froth flotation (a process with a much longer history, going back to its first application in 1905). This is the reason for some of the initial skepticism of some eminent researchers during the early 1970s, who found it difficult to believe that metal-hydroxide flocs would attach to DAF bubbles at all (Gregory 1997). To some extent, recent modelling supports this concern, as the collision efficiency between negatively charged bubbles and flocs is indeed very low. Trajectory modelling of flocs and bubbles in the contact zone, verified by experiment, showed conclusively that the relative surface charge of the flocs and bubbles is the single most important parameter affecting the collision efficiency factor (Han 2002). If the charge on DAF bubbles could be altered, the efficiency of DAF could be improved tremendously; some work on the charge reversal of bubbles has already been reported (Han *et al.* 2004).

PRETREATMENT

Heinänen *et al.* (1995) provided a simple raw surface water classification, which recognises *humic* waters, often with low temperature (strongly evident in Scandinavia, Finland, parts of England and the northeastern USA), *eutrophic* waters with high algal and organic concentration (strongly evident in warm dry climates with a high level of indirect reuse) and *turbid* waters with (occasionally) high loads of inorganic solids. DAF is not particularly suitable for dealing with high inorganic turbidity, but eminently so for dealing with either humic or eutrophic waters. This was already evident from the previous section, where the early successes of DAF in Scandinavia and Finland can be traced to the prevalence of cold, humic water, and those in Windhoek to the occurrence of high algal concentrations in warm maturation pond effluent.

DAF pretreatment was initially closely patterned after that of sedimentation, which used time-tried guidelines for long enough flocculation times to provide for large flocs which would settle quickly. Gradually it was realised DAF does not need such large flocs and the flocculation time was consequently reduced. By the early 1990s, flocculation times of less than 5 min were propagated, compared to the typical flocculation time of about 20 min used in the early 1970s. At the same time, DAF benefited from general advances made in coagulant chemistry and flocculation research. Extensive research at a fundamental level and pilot scale during the 1990s, notably the work guided by Edzwald at the University of Massachusetts, brought about the much improved understanding we have today (for example, Edzwald & Wingler 1990; Edzwald *et al.* 1992; Valade *et al.* 1996).

MODELLING OF THE CONTACT AND SEPARATION ZONES

Numerous modelling approaches have been applied to the complex process of how bubbles and flocs interact. The interaction was modelled as two consecutive steps. The first step modelled the contact zone, where the principal objective was to predict the collision and attachment efficiency between bubbles and flocs, while the second step modelled the separation zone, where the objective was to predict the buoyancy and rise rate of bubble–floc agglomerates.

For contact zone modelling, two different approaches were used. The first approach viewed the contact zone as a bubble bed which moves upward through the floc suspension, analogous to a particle suspension moving downward through a sand filter. Drawing on filtration theory, with appropriate adjustments, a floc removal rate expression was obtained (Edzwald 1995). The second approach views the contact zone in terms of the initial populations of flocs without bubbles, and flocs with bubbles. Expressions are derived for the rates at which the first population declines and the second population grows–analogous to the kinetic flocculation models which describe the conversion of primary particles into flocs. These expressions required kinetic constants, which were correlated with the turbulent fluid shear in the contact zone (Fukushi *et al.* 1995).

For separation zone modelling, the basis was found on modified versions of Stokes' law. Numerous assumptions were required to obtain a workable model, namely functions for floc density, drag forces on floc–bubble agglomerates, bubble sizes, bubble packing density on flocs, Reynolds number, etc (for example, Haarhoff & Edzwald 2004). Moreover, the models had to be based on static conditions where neither bubbles nor flocs grow or shear during separation.

Many modelling papers, broadly following the approaches above, have appeared in the literature. The models, however, require calibration constants which cannot be theoretically predicted. Also, there is a growing awareness that the contact processes extend well into the separation zone and that the contact and separation zones are neither separated in space nor independent. Despite all these misgivings, DAF modelling has been highly instructive by illuminating the roles of the numerous design and operational parameters and by providing the theoretical underpinning for much of what is observed in practice. There is now a better understanding of the relative importance of bubble and floc sizes, bubble and floc concentrations, water temperature, hydraulic loading in the contact and separation zone, etc. Most importantly, it has been demonstrated that the ultimate efficiency of DAF depends heavily, as with other water treatment processes, on the chemical pretreatment. Small changes in the attachment efficiency factors will lead to large changes in DAF efficiency, making the optimisation of coagulant selection and dosing as important as the design of the DAF reactor itself.

TOWARDS HIGHER RATES AND PROCESS COMBINATIONS

Prior to the 1970s, sedimentation was exclusively used as the phase separation step before filtration. The early DAF research was thus driven by comparative testing to determine whether DAF could be as cost-effective as sedimentation. Numerous studies convincingly showed that DAF had significant advantages for some specific raw water types (for example, Gregory 1976). Having established the superiority of DAF for some raw water types, the next challenge was to retrofit it to existing water treatment plants, a problem existing to this day–building new treatment plants from scratch is relatively rare compared to extension and upgrade projects at existing treatment facilities. In Latin America, for example, 20 DAF plants were commissioned between 1992 and 2000, of which nine were retrofits at previously existing treatment plants (Richter & Gross 2000). As the hydraulic loading of the DAF separation zone was fairly similar to that of rapid filtration, an early, fairly obvious development was to place both processes in the same reactor, with DAF separation taking place in the headspace above the filter media. Besides the obvious savings in space and capital, a further benefit was the stabilisation of the hydraulic pattern induced by the perfectly even flow into the media. This variation was first used at full scale by the very end of the 1960s in Sweden (Kiuru 2001) and was labelled as the FLOFILTER. This option has gained wide acceptance. Of the nine retrofits in Latin America mentioned above, eight used the FLOFILTER principle. A decade later, the same process was extensively investigated at pilot scale in South Africa under the name DAFF (dissolved air flotation filtration), followed by a partial retrofit at full scale in 1984 (Vosloo *et al.* 1986) and the first full retrofit in 1988 (Haarhoff & Fouche 1989). The process found wide application. For example, 20 DAFF plants were constructed in Australia between 1980 and 1996 with all but one performing admirably (Finlayson & Huijbregsen 1997). Another FLOFILTER variation was recently successfully demonstrated in China, using GAC as the filter medium (Zhang *et al.* 2004). The FLOFILTER remains a popular choice (Joshi *et al.* 2005) and will likely be so in the future. The new treatment plant now being built in New York which will be the largest DAF plant in the world, for example, will be a FLOFILTER facility above a bed of anthracite and sand (Crossley *et al.* 2007).

The first DAF systems relied on co-current flow–both flocs and bubbles were introduced at the bottom of the contact zone and formed agglomerates as they ascended towards the float layer. In the middle of the 1980s, a package-plant supplier in South Africa installed some plants with counter-current flow, where the flocculated raw water was introduced at the top of the separation zone and the saturated recycle at the bottom, thus obviating the need for a separate contact zone. This principle was applied to both small DAF and later DAFF reactors (Offringa 1995). During the 1990s the independent development of counter-current DAFF, under the wings of a large international supplier, took a huge step forward when it was comprehensively tested at pilot-scale for three years and re-engineered for large-scale municipal water treatment under the label COCODAFF. The process was first used at full scale in 1995 and has since been applied at some large treatment plants in South Africa and the United Kingdom (Eades *et al.* 1997; Officer *et al.* 2001).

The principal weakness of DAF as a phase separation process is that it cannot readily deal with high levels of inorganic turbidity–the flocs become too heavy and unstable to be buoyed up for long periods. The threshold value for DAF had been traditionally accepted at about 100 NTU, a value confirmed by recent work performed in Korea (Kwon *et al.* 2004). In an exceptional case, DAF could successfully deal with extreme turbidity levels of 4,000 NTU, provided that coagulation is carefully controlled (Richter & Gross 2000). In general, however, it becomes necessary to precede DAF with a more robust process such as sedimentation when dealing with the common problem of raw surface water sources that are subject to extreme but short-lived turbidity peaks during flood events. In South Africa, the combination of sedimentation ahead of DAF was first applied at the 60 Mℓ/d Vaalkop water treatment plant in 1999. The same process sequence, more recently, was successfully tested in Korea under the label SEDAF (Chung *et al.* 2000; Kwon *et al.* 2004; Kwak *et al.* 2005) showing great promise for sources with highly variable quality, provided that the system is very carefully operated during the rainy season.

DAF is eminently suitable for the removal of powdered activated carbon, often added at South African water treatment plants for intermittent taste and odour control. A novel DAF/sedimentation combination is to use the DAF *ahead* of sedimentation when powdered activated carbon (PAC) is used on eutrophic raw water. Fresh PAC is dosed after DAF and removed during a lamella-assisted sedimentation step, with the PAC-enriched sludge then recycled to the inlet of the plant. The PAC is then removed for a second time in the DAF reactor before being disposed of, allowing for the counter-current two-stage use of expensive PAC to fully utilise its adsorption potential. This PACDAF system was first introduced at full scale in South Africa during the 1990s (Offringa 1995).

A logical quest is to increase the hydraulic loading rate, which translates directly into a smaller footprint and reduced capital costs. When DAF was introduced into water treatment in the 1960s, it was patterned as an alternative to sedimentation with loading rates of less than 5 m/h – barely higher than sedimentation. As experience and confidence was gained, bolder and progressively higher rates were adopted. By 1992, a survey of published literature indicated maximum full-scale loading rates of 11 m/h (Haarhoff & Van Vuuren 1993), with a Belgian plant then actually running at 15 m/h (later reported by Kempeneers & Van Menxel (2001)). In 1994, pilot tests were reported that investigated rates of 18 m/h for Calgary (Vallance *et al.* 1995) and 20 m/h for Boston (Johnson *et al.* 1995). By 2000, the design of full-scale systems was underway at rates of 18 m/h for Boston (Crossley *et al.* 2001), 20 m/h for New York (Nickols *et al.* 2000), 18 m/h for Winnipeg and 16 m/h for Vancouver (Adkins 1997). A Finnish development emerged in 2000 which was described as turbulent flotation, under the commercial name of RE-FLOW flotation (Suutarinen 2000). This claimed that rates of 30–40 m/h were feasible without any changes to the bubble sizes typical for DAF, and that 60 m/h could be reached with larger bubbles and deeper tanks (Kiuru 2001). At these high rates, two problems have to be solved. First, the flow pattern in the separation zone needs to be stabilised. This can be achieved at pilot scale by introducing lamella plates within the separation zone, called HR-DAF (Reali & Marchetto 2001). The RE-FLOW system uses a thin stiff horizontal plate at the base of the separation zone with patented orifices which will ensure a perfectly even vertical flow in the lower part of the tank (Kiuru 2001). The second problem is to prevent residual air bubbles from being drawn into the outlet. A solution to this problem is provided, for example, with the DAF–RAPIDE system, which traps the unwanted air with a series of lamella plates at the bottom of the tank just before the outlet (Amato *et al.* 2001).

The versatility and scalability of DAF led to numerous practical innovations, which are only briefly enumerated for lack of space:

- Where it is practical to construct deep tanks, the DAF reactor had been suspended over the flocculation compartment, notable the FLOTAPUR system from

Finland (Takko 2000*a*) or the TRIPLE-DECK system used in the United Kingdom (Stephenson 1997).

- Where ozonation is practiced, it offers the opportunity to use the ozone-rich bubbles to serve a simultaneous flotation function. Two methods have been developed in France–the OZOFLOT process, where the bubbles emerging from a diffuser are fragmented into small microbubbles by creating high turbulence above the diffuser, and the FLOTTAZONE process, which releases supersaturated ozone from a recycle stream using normal nozzles. The latter process has been successfully applied at full scale in 1995 (Baron *et al.* 1997).
- With increasing attention to the proper management and recovery of water treatment plant residuals, DAF has been successfully applied in a number of cases. It was shown to be highly effective for concentration of water treatment sludges (Reali *et al.* 2000; Bourgeois *et al.* 2004; Dockko *et al.* 2006) as well as for the recovery of filter backwash water (Eades & Bates 2001).
- DAF has been shown to be the most suited pretreatment for reducing the fouling of subsequent microfiltration in studies focusing on wastewater reclamation (Chuang *et al.* 2005) and water treatment (Van Benschoten *et al.* 2002).

HYDRAULIC FLOW PATTERNS IN THE SEPARATION ZONE

The hydraulic flow pattern in the DAF separation zone is complex. The decades of experience gained with sedimentation tank design offered no benefit to the early designers of DAF systems, despite the loading rates being of the same order of magnitude. This is due to the suspended air in the suspension which caused much larger gradients in density than experienced in sedimentation. The flow pattern in a DAF tank with recycle (closer to plug flow) is completely different from the pattern without recycle (closer to completely mixed flow). What does this flow pattern look like? The work at the University of Lund in Sweden provides the most recent and complete picture at present (Lundh *et al.* 2001; Lundh & Jonsson 2005). There is a strong horizontal current on the surface from the contact zone towards the far wall with a horizontal return current immediately below (a condition termed as a "stratified" condition). In the bottom section of the tank the flow is more or less vertical. When either the hydraulic loading rate is increased, and/or the recycle rate is decreased (in other words, when the air/water ratio was lowered), the forward horizontal current is drawn below the surface towards the outlet with a much more haphazard return current (termed a "short-circuit" condition). The air concentration in the lower parts of the separation zone is much higher during the short-circuit condition, thus posing a greater danger of being drawn into the effluent. There is a strong relationship between the recycle rate, the hydraulic loading rate and the degree of short-circuiting. As higher loading rates are used, more recycle (air) is required to prevent short-circuiting.

The experimental work, despite the insights that it brought, did not exhaust all the possible scenarios. The experiments were conducted in a smallish pilot tank of shallow depth, using a clear suspension. The effect of the separation zone depth was not varied; also, the flow pattern in the separation zone had been observed to stratify better at higher concentrations of suspended solids in the raw water (Lundh 2002) or when the coagulant dosing is turned off (Haarhoff & Edzwald 2004). Further experimental work is required to illuminate the roles of depth, solids content and coagulant dosing.

The pivotal concept that was developed from the studies at Lund University is that of flow *stability*. This was recognised since the time when designers started to provide multiple drawoff points evenly spread at the bottom of the separation zone to minimise the disruption to the bubble bed and to prevent air from being drawn into the outlet. The development of the FLOFILTER/DAFF concept, although primarily aimed at reducing costs, had the additional benefit of ensuring a perfectly even drawoff rate at all points in the tank due to the media bed below the separation zone. It was only in recent years, when DAF was challenged with very high loading rates, that flow stability became an issue again. The use of a horizontal perforated plate for flow withdrawal had been mentioned earlier in this paper. Recent research had to be re-directed to such basics such as deliberate attempts to approach plug flow (Liers & Baeyens 2001), optimum length:width ratios and the effects of the bubble bed depth (Han *et al.* 2007).

The research in this vitally important area is hampered by a lack of sufficiently sophisticated tools. The time-tried visualisation of flow patterns does not work well in a tank filled with an opaque, milky suspension. Velocity measurement techniques such as acoustic Doppler velocimetry (ADV) are intrusive and necessarily affect the flow patterns in their immediate surroundings. Although laser Doppler anemometry (LDA) does not intrude, it is limited in its depth of penetration. Direct viewing of the bubbles with a borescope offers an instructive, but severely limited, view of a small local region. Mathematical modelling with computational fluid dynamics (CFD) holds great promise, although it relies on numerous assumptions and simplifications, some which may be questionable. Residence time distribution (RTD) analysis, as obtained from tracer tests, is reliable, but only yields partial insights. To their credit, many researchers have persevered with these studies, despite these inherent difficulties, to which we owe much of our current understanding. Slowly but steadily, however, the methods are continuously refined and better convergence between the different approaches is reported. There can be no doubt that our understanding and predictive ability of separation zone hydraulics will greatly improve in the next few years.

IMPLEMENTATION OF DAF AT FULL SCALE

Hundreds of DAF water treatment installations have been built in many parts of the world. Some of these installations have been abandoned, while the growth in new installations had not been as rapid as anticipated. The overall number of DAF installations, however, continues to grow. Of special significance is the number of large installations. Large water utilities will not invest large amounts of capital and make themselves dependent on DAF if they do not have complete faith in the process. Using an arbitrary yardstick of 50 Mℓ/d or more to identify "large" plants, a compilation of large plants is shown in Table 1, providing convincing evidence of how generally DAF has been accepted by the international water community. The cumulative treatment capacity represented by the plants shown in Table 1 is shown in Figure 1. The total installed capacity has recently exceeded the 10,000 Mℓ/d mark.

HOW DO WE ACCEPT A NEW TECHNOLOGY?

Drawing on the developments described in this paper, we return to the central question posed in the beginning–how far has DAF developed? This question was also pursued at earlier meetings. In 1976, DAF was perceived to be an "art" rather than a "science". At the London Conference in 1997, the carefully worded hope was expressed that "most of the perception should have been dispelled" by the advances between 1976 and 1997 (Gregory 1997). At the Helsinki Conference in 2000 a bolder opinion was voiced that DAF "may be considered a mature technology", although "there is still considerable scope for research and development to make the process even more efficient" (Schofield 2001). So where are we seven years later?

A generic model of product/technology acceptance was proposed by Moore (1991). This model, depicted in Figure 2, was found to hold true for many technologies (Sroufe *et al.* 2000). The natural progression is the adoption by a few "innovators" at first, followed by a slightly larger group of "early adopters". The bulk of the technology users are in the "early majority" and "late majority" categories, followed by a much smaller group of "laggards". The single strongest point of resistance in this progression is moving from the "early adopters" to the "early majority"–a resistance point which is labelled as the "chasm". For technology developers, the principal challenge is that of "crossing the chasm". The end of the cycle is reached when the technology is fully accepted, or displaced by another.

Water treatment plants require long lead times to plan, test, design and construct, and have lifespans of decades once they are built. The first point to note, then, is that the entire product cycle in Figure 2 will run over a few decades rather than the few years for the adoption of fax machines, for example. Moreover, water treatment plants are only built when increased demand warrants the effort. Even if water treatment professionals fully endorse DAF as the preferred option, it may take many years before the opportunity arises to exercise this option. Despite these misgivings, the Moore model is useful in providing some structure to this analysis.

In terms of the Moore model, the following periodisation of DAF development is offered:

Table 1 | List of DAF plants with capacity of more than 50 Mℓ/d

Location	Country	Completed	Capacity (Mℓ/d)
Richards Bay	South Africa	1985	120
Brisbane	Australia	1986	250
Pittsfield, MA	USA	1987	91
Graincliffe	England	1993	60
Frankley	England	1994	450
Headingley	England	1995	120
East London	South Africa	1995	120
Bradan	Scotland	1997	142
Fairfield CT	USA	1997	189
Caraguatuba, Sao Paulo State	Brazil	1998	51
Melaka	Malaysia	1998	140
Ipo	Malaysia	1999	275
Tampere	Finland	2000	72
Maldonado	Uruguay	2000	173
Punta del Este	Uruguay	2000	170
Greenville, SC	USA	2000	284
Vaalkop	South Africa	2001	180
Cambridge, MA	USA	2001	91
Felindre	Wales	2001	273
Antwerp	Belgium	2002	150
Wonju	South Korea	2002	200
Cumberland, MD	USA	2002	57
Lake De Forest, NJ	USA	2002	77
Manaus, Amazonas State	Brazil	2003	310
Curitiba City, Parana State	Brazil	2003	360
Turku	Finland	2003	86
West Nyack, NY	USA	2003	76
Barrow	England	2004	120
South San Joaquin, CA	USA	2004	177
Minera Escondida Ltd.	Chile	2005	92
Maundown	England	2005	84
Newport News, VA	USA	2005	204
St George, UT	USA	2005	159
Boulder, CO	USA	2005	61
Quingzhen	China	2006	106
Yorkshire	England	2006	114
Fofanny	Ireland	2006	55
Brasov	Romania	2006	173
Rosebery	Scotland	2006	60
New Haven, CT	USA	2006	57
White Tanks Ltd., AZ	USA	2006	77

Table 1 | (*continued*)

Location	Country	Completed	Capacity (Mℓ/d)
Vitoria, Espirito Santo State	Brazil	2007	240
Vitoria, Espirito Santo State	Brazil	2007	50
Westbank Powers Creek, BC	Canada	2007	55
Tianjin	China	2007	500
Jekaterinburg	Russia	2007	168
United Arab Emirates, seawater	United Arab Emirates	2007	264
Stamford CT	USA	2007	114
Livermore, CA	USA	2007	57
Belo Horisonte, Minas Gerais State	Brazil	2008	104
Brasilia	Brazil	2008	240
Aracatuba, Sao Paulo State	Brazil	2008	360
Alto Sertao, Sergipe State	Brazil	2008	50
Castor Bay	Ireland	2008	115
Dunore Point	Ireland	2008	115
Mourne	Ireland	2008	155
Marchbank	Scotland	2008	62
Sao Bernardo, Sao Paulo State	Brazil	2009	690
Winnipeg	Canada	2009	400
Vernon, BC	Canada	2009	155
Penticton, BC	Canada	2009	115
Waco, TX	USA	2009	341

- The DAF "innovators" were those that experimented and started to apply DAF as a new option in the 1960s and early 1970s, before there was a consolidated body of supporting knowledge as we have today.
- The "early adopters" were those that applied the process at full scale between about 1975 and 1985. The 1976 Conference may have been a stimulant is this regard, having demonstrated that DAF was indeed a credible technology embraced by many others all over the world.
- The "chasm" seems to have been the period roughly between 1985 and 1995. Although many smaller plants were commissioned all over the world, the technology

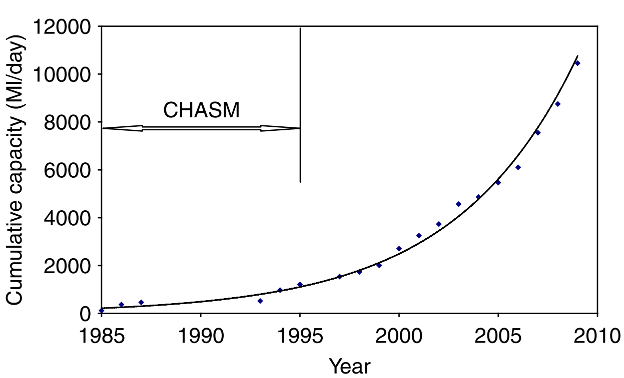

Figure 1 | Cumulative installed DAF capacity represented by the large treatment plants (>50 Mℓ/d) listed in Table 1.

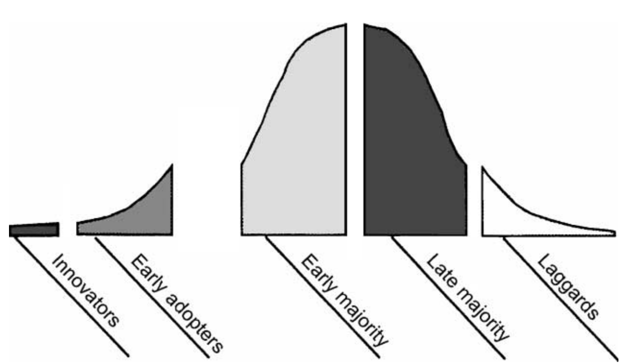

Figure 2 | Phases in the adoption of a new product or technology (after Moore 1991; taken from Sroufe *et al.* 2000).

was stagnant and utilities, except possibly those in Sweden and Finland, seemed hesitant to fully endorse the process at larger scale. The 1994 Orlando Conference, with its impressive display of new studies, ideas and consolidated understanding, may have been instrumental in dispelling many doubts about the process to bring the "chasm" to an end.

- The era of the "early majority" dawned in the early 1990s when a number of larger utilities turned their serious attention to DAF, clearly evident from Figure 1. With so much more at stake in large cities like New York and Antwerp, for example, much more stringent pilot testing had to be performed beforehand.

This "early majority" era is not only evidenced by the increase in large plants being built, but also by a rapid pushing of the technology to new regions of higher loading rates and better understood coagulation and flocculation requirements. How far we have presently progressed into or even beyond the "early majority" era, only history will tell. Many more utilities will probably adopt the process when opportunities for expansion or upgrading present themselves. The literature reviewed showed limited DAF acceptance in Asia, but a wave of research and fresh ideas now coming from Asia should soon swell the DAF applications in this region. An internet search for DAF journal papers, using a reputable international database, showed that 16% of the total number of journal papers in 1998–2000 came from Asia; 26% in 2001–2003; for the period 2004–2006 this rose to 45%. Most notable was a surge in papers from South Korea.

Following the premise of the Moore model that "crossing the chasm" is the critical point in the acceptance of a technology, the conclusion is therefore drawn that DAF has now clearly moved beyond this point. Researchers, designers, suppliers and operators can now concentrate on the systematic refinement of DAF for water treatment to achieve even better operational and cost efficiency.

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