The design and operation of conventional and novel flotation systems on a number of impounded water types

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Abstract This paper describes the design of conventional Dissolved Air Flotation (DAF) systems, and the novel Counter Current Dissolved Air Flotation Filtration (COCODAFF®) process. The operation and performance of these plants on a variety of water types in the United Kingdom and South Africa is also described. The advantages of flotation processes for the treatment of impounded waters either high in colour, or with a high concentration of algae, is discussed. Other topics covered in this paper are hydraulic flocculation, and the application of Finite Element Analysis (FEA), to the design of flotation plants. It is concluded that the COCODAFF® process offers a number of advantages over conventional DAF systems.

Keywords Algae; COCODAFF®; flotation; FEA.

Introduction
Dissolved air flotation is now an established process in the United Kingdom, Continental Europe, Australia and South Africa. There are a number of variations in the design but most systems operate on a co-current principle, in which the recycle is introduced such that the water flow and the developing microbubbles are initially moving in the same direction. In the earlier units the flotation cell was separated from the filter units but today combined flotation/filtration units are becoming more common.

The conventional arrangement is to introduce the flocculated water into the DAF unit via a riser section (attachment zone), with the recycle returned to the base of the riser. There is intimate contact between the floc particles and the microbubbles in the riser section as the water flows vertically upwards before entering the flotation cell over a submerged weir (see Figure 1).

More recently in the United Kingdom and South Africa, the counter current method of flotation has been developed by Thames Water (Eades et al., 1993, 1997; Eades and Brignal, 1995). Flocculated water is distributed evenly below the surface of the COCODAFF® units by a system of submerged laterals and distribution cones (see Figure 2). The recycle water is distributed uniformly over the COCODAFF® area below the inlet cones by an array of recycle nozzles. The flow of the flocculated water is counter-current to the rising microbubbles promoting greater bubble particle interaction than in a conventional DAF process. The first plant at Walton in England was successfully commissioned and went into production in March 1995. A number of other plants are currently in operation or are under construction.

In order for the COCODAFF® process to operate successfully it is essential that the flocculated water be evenly distributed across the area of the unit otherwise short circuiting and rolling will occur leading to poor performance. Similar consideration must be given to the distribution of the microbubbles. Extensive research has been carried out in the UK into these aspects of the process using Finite Element Analysis in order to develop the inlet system (Eades et al., 1997). Special recycle nozzles have also been developed to provide a uniform distribution of microbubbles.
This paper describes five flotation plants, two of which are conventional DAF plants, while the remaining three are COCODAFF®. Recent work on flow distribution and FEA is also described.

**Conventional flotation**

The conventional DAF plants described in this paper are Farmoor WTW (109 Ml/d) in Southern England, operated by Thames Water, and Carron Valley WTW (125 Ml/d) in Scotland, operated by East of Scotland Water. Farmoor WTW treats reservoir stored water derived from the River Thames, which is a typical lowland source of high alkalinity and subject to seasonal blooms of algae. Carron Valley WTW treats reservoir stored water derived from the Rivers Carron and Endrick, which is a moderately coloured upland water of low alkalinity and hardness and which is subject to moderate blooms of algae.

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**Figure 1** Schematic diagram of the conventional DAF Process

**Figure 2** Typical arrangement of a COCODAFF® unit
Farmoor WTW

The works, which is located approximately four miles south west of the city of Oxford in the UK, treats River Thames water from Farmoor reservoir. The raw water is moderately hard with turbidity values typically around 3.5 NTU and a colour of 9 Hazen. During the summer months the reservoir is subject to algal blooms with chlorophyll-a values reaching 70 µg/l. The original works, comprising four Permutit precipitators and nine rapid gravity filters, had a maximum output of 67 Ml/d. During the seasonal algal blooms, the output of the works was severely restricted as a result of short filter run times, typically eight hours, and the treated water quality deteriorated. The new extensions were designed to address these problems and to increase the output of the works to 109 Ml/d. Extensive pilot plant trials were carried out with pre-ozone, DAF, rapid gravity filtration, main ozone and GAC. As a result of these trials, the precipitators were down-rated to 44 Ml/d, and a 72 Ml/d conventional DAF stream was constructed in parallel. Each stream comprises five units rated at 7.2 m/h, each with two-stage mechanical flocculation and hydraulic desludging. The rapid gravity filters were up-rated to an average of 7.8 m/h and modified to a combined air/water wash. The filter media used is 800mm of 0.6 to 1.18mm grade sand. Pre-ozone, main ozone, and GAC contactors were added to the process train.

It has been found that the pre-ozone improves the performance of the DAF units and reduces the coagulant demand by up to 30%, depending on raw water conditions. Floated water turbidity is typically 0.4 NTU when the pre-ozone is operating and 0.6 NTU without pre-ozone. This is slightly better than the 0.8 NTU predicted by the pilot plant trials. Water for the DAF recycle is drawn from the filtered water channel and is passed through self cleaning screens before entering the absorber vessel. Clarified water from the precipitator and DAF streams combines before the filters but the blend is incomplete before filtration, some filters receiving water mainly from one stream. Filter run times in excess of 24 hours are now maintained even during the most severe blooms of algae. During these periods, the DAF sludge becomes sticky due to the accumulation of algae but this has not affected the hydraulic sludge removal. A summary of raw and treated water is presented in Table 1. The performance of the DAFs exceeded expectations such that the maximum throughput of the DAF stream has been increased by 25% to 90 Ml/d, whilst maintaining the required water quality.

Carron Valley WTW

Carron Valley WTW is a new treatment works commissioned in August 1998 and built adjacent to an existing works, which comprised hopper-bottom upflow clarifiers and rapid gravity filters. The old works, which has now been de-commissioned, was giving problems due to sludge blanket instability, short filter run times, and high aluminium residuals in the final water. The raw water, which is subject to moderate algal blooms, has an alkalinity of 20 mg/l, a colour of 35 Hazen, and a turbidity of 1.7 NTU. Trials were carried out in 1993 using a conventional DAF pilot plant and rapid gravity sand filter. The DAF pilot plant was operated at 10.2 m/h and the filter at 10.4 m/h. Aluminium sulphate and ferric sulphate coagulants were used during the trial. When the plant was operating on ferric sulphate, the turbidity of the subnatant averaged 0.6 NTU with an iron residual of 0.35 mg/l, and on aluminium sulphate an average turbidity of 0.7 NTU with an aluminium residual of 0.3 mg/l was obtained. Polyelectrolyte (Allied Colloids LT 22) was also tried but appeared to give no advantage. The pilot trials confirmed that DAF was a suitable process for treating water from the Carron Valley reservoir.

At the new Carron Valley WTW, the process train comprises coagulation with aluminium sulphate, two-stage mechanical flocculation, conventional flotation with hydraulic desludging, rapid gravity filtration (1200mm of 0.8–1.7mm sand with combined air/water
wash), and final disinfection with chlorine. Polyelectrolyte can be dosed either to the flocculators or to the clarified water. There are eight DAF units rated at 9.2 m/h, and eight filters rated at 10.0 m/h. The recycle is drawn from the clarified water channel and is passed through self cleaning screens before entering the air absorption vessels. The performance of the works has been somewhat better than predicted by the pilot trials. DAF subnatant turbidity is typically 0.4 to 0.5 NTU with an aluminium residual of 0.2 mg/l. It has been found that by increasing the pH before filtration from 6.1 to 6.7, excellent filtration performance is obtained. Filter run times are typically 60 hours with a filtrate turbidity of <0.1 NTU, and an aluminium residual of 0.02 mg/l. On the main plant, polyelectrolyte has been found to improve performance of both floaters and filters by reducing turbidity and aluminium levels. A dose of approximately 0.2 mg/l is applied at the inlet to the flocculators.

Counter-current dissolved air flotation (COCODAFF®)

In the COCODAFF® process, recycle containing the dissolved air is introduced below the inlet distribution so that the released air forms a “bubble blanket” moving counter-current to the water (Figure 2). Floc is progressively removed and floated to the surface as the flocculated water migrates downwards through the bubble blanket. The filter, which is located at the base of the flotation cell, can be either dual or monomedia depending on the particular application. The advantages of the COCODAFF® process are that any fall-out of sludge during the desludging process is recaptured in the bubble blanket and floated back to the surface. The recycle is introduced at a point in the process where most of the floc has already been removed, and this avoids the potential for floc damage around the high shear area of the recycle input. There is also evidence of flocculation occurring in the upper levels of the flotation cell. Mechanical flocculation upstream of the flotation cell is therefore not required with COCODAFF® and excellent performance is obtained utilising hydraulic flocculation. Stored reservoir waters, which are subject to seasonal blooms of algae, may be suitable for direct filtration for most of the year but require a flotation process to maintain filter run times when algal counts are high. In such cases the COCODAFF® process can be operated in direct filtration mode with the flocculator by-passed during periods of low cell counts. Should the numbers of algae increase, the flotation process can be quickly brought on line. Having both flotation and filtration processes accommodated in the same structure results in a very compact process. The COCODAFF® system has the potential to be fitted into an existing filter provided there is sufficient depth available.

The COCODAFF® plants described are Walton WTW in Southern England (135 Ml/d), which treats reservoir stored water from the River Thames, Klipdrift WTW in South Africa (18 Ml/d), and Ballinrees WTW (30 Ml/d) in Northern Ireland.

Ballinrees WTW

The works treats water stored in the Ballinrees reservoir, which is fed from upland springs and, during the summer months is supplemented with water pumped from the river Bann. The upland source is highly coloured, typically 200 Hazen, with a turbidity of 1.0 NTU and an alkalinity of 36 mg/l. The River Bann water is less coloured, typically 70 Hazen, with a turbidity of 3.0 NTU and an alkalinity of 76 mg/l. The feedwater to Ballinrees is therefore highly variable since the reservoir is small (approximately 70 acres in area) and short-circuiting does occur. The reservoir is also subject to seasonal blooms of algae with counts of approximately 9000 cells/ml.

The original Ballinrees works consisted of ten hopper-bottom clarifiers, one Centrifloc clarifier and 16 rapid gravity filters. Problems associated with the old works included blanket instability on the clarifiers due to the light nature of the floc, and the absence of a dedicated manganese removal stage. During the construction of the new works, the
Centrifloc was demolished and five COCODAFF® flotation cells were built in the space made available. During this period the hopper bottomed clarifiers and filters remained in service until the COCODAFF® plant was commissioned. After commissioning, the clarifiers were demolished, and the rapid gravity filters were refurbished and brought back into service as a dedicated manganese removal stage. The COCODAFF® flotation stage is rated at 5.5 m/h and produces a subnatant of approximately 1.0 NTU. The COCODAFF® filters, which are rated at 6.1 m/h, are charged with 1000mm of sand media grade 0.85–1.7mm and are washed with a combined air/water wash. Mixing and flocculation are achieved hydraulically in a single vessel with a nominal retention time of 15 minutes. The coagulant is aluminium sulphate, which requires pH correction with lime when the upland source is being used. A dose of 0.04 mg/l polyelectrolyte is applied at the flocculation stage and represents a 75% reduction in the use of polyelectrolyte compared with the old plant. The flotation units are de-sludged hydraulically using backwash water. The turbidity of the COCODAFF® filtrate is typically < 0.1 NTU with an aluminium residual of 0.02 mg/l. Algae removal typically exceeds 98% with filter run times of approximately 30 hours.

Walton WTW
Walton WTW treats River Thames water from the Knight, Bessborough, and Queen Elizabeth II reservoirs. The raw water, which is moderately hard and low in turbidity and colour, is subject to blooms of algae. The original works, comprising rapid gravity filters followed by slow sand filtration, had a maximum output of 135 Ml/d. The rapid gravity filters were ageing and were not giving the required performance, especially during seasonal blooms of algae, when the much reduced run times caused operational problems. Extensive pilot plant trials were carried out prior to the selection of the COCODAFF® process for the Walton project. The pilot plant, which had a flotation area of 4 m², was tested at rates of 10 to 15 m/h with ferric sulphate as the coagulant. A number of inlet designs were tested and the final selection, an inverted cone, was made on the basis of pilot plant performance and flow modelling. To suit the counter-current mode of operation, a new type of recycle nozzle, which directs the recycle in a radial direction, was developed during the pilot plant trials. Following the pilot trials the decision was made to design a 145 Ml/d COCODAFF® plant consisting of 12 COCODAFF® units rated at 10 m/h. These are fed from two flocculators each providing a nominal 15 minutes hydraulic flocculation. The floated sludge is removed hydraulically using flocculated water. The filters are dual media with 600mm sand, grade 0.6 to 1.18mm, and 600mm of No 2 anthracite. The media is washed with combined air/water followed by a regrade. During periods of good raw water quality the flocculators are by-passed, the recycle turned off and the COCODAFF® units are operated in contact filtration mode. Ozone can be dosed both upstream and downstream of the COCODAFF® plant, the second stage ozone being followed by GAC with a 15 minute empty bed contact time. The works has been designed with sufficient hydraulic capacity so that in the future the COCODAFF® units may be operated at up to 15 m/h if additional output is required and the process performs to expectations.

Klipdrift WTW
The works is operated by Magalies Water and treats water from the Roodeplaat Dam, which is approximately 35 km from the works. The water is transferred for approximately half of the distance in an open channel and half by pipeline. At the old works the water was treated by coagulation with ferric chloride followed by sedimentation and rapid gravity filtration. The raw water, which is moderately hard, is normally of low turbidity but is subject to blooms of algae. The algae caused problems on the rapid gravity filters, which were of single sand media and approximately 25 years old. The new plant is the first COCODAFF®
plant to be built in South Africa and was designed by Paterson Candy International (SA). The original plant design was for filters for which Paterson Candy were supplying the filter floor as a sub contractor. Magalies Water and their consulting engineers Stewart Scott then took the decision after visiting Walton WTW, to use the COCODAFF® process, and Paterson Candy designed the COCODAFF® cells to suit the application. The new development at Klipdrift WTW comprises three COCODAFF® units each rated at 7.61 m³/h and fed from three dedicated flocculators each providing a nominal 15 minutes hydraulic flocculation. The floated sludge is removed hydraulically by closing the filter inlet and outlet valves and directing the flocculated water across the unit to carry the float to the sludge discharge channel. The COCODAFF® filters are dual media with 500mm of sand grade 0.6 to 1.18mm, and 300mm of No 2 anthracite. The filters are washed by a separate air scour and water wash.

Table 1  Summary of DAF and COCODAFF® performance data.

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<th>Treatment plant</th>
<th>Parameter</th>
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<td>(DAF)</td>
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Flotation tank design
It is not possible to cover all aspects of the design in this paper but design features which have only recently been the subject of more detailed investigation are the introduction of the recycle and flow distribution in the attachment and flotation zones. These investigations have been carried out using underwater cameras, visual dye tests and Finite Element Analysis (FEA).

Conventional DAF
Work has been carried out on tank geometry and the effects of flow distribution in the attachment and flotation zones (Fawcett, 1997; O’Neill et al., 1997; Jonsson et al., 1997; Ta and Brignal, 1997). Important considerations are the height of the inlet slot and the width of the attachment zone. A sloping baffle tends to promote recirculation in the attachment zone. Positioning of the recycle nozzles is important in order to prevent backfeed of air bubbles into the flocculation tank at low plant flowrates. The length to depth ratio (l/d) of the flotation cell was also found to influence the flow pattern within the cell. It was observed that strong recirculation occurs at low l/d ratios, while a diagonal flow pattern is favoured at high l/d ratios. The author’s experience is that shallow tanks tend to produce a better quality water than deeper units.

COCODAFF®
In the COCODAFF® process it is important that there is uniform distribution of flow via the inlet system into the flotation cell. A number of inlet systems have been investigated and currently an inverted cone arrangements favoured (Figure 2). From purely cost considerations it is an advantage to reduce the depth of the flotation cell. In process terms the poten-
tial disadvantages of reducing the depth are to reduce the bubble-floc contact zone thus lowering the probability of solids capture, and to bring the inlet system into closer proximity to the floating scum thereby increasing the risk of solids knockdown. If the flow distribution can be fully optimised a shallower contact zone may be possible, and if localised inlet velocities are either prevented or re-directed it may also be possible to bring the inlet system closer to the floating scum.

Work on these aspects of the design is currently being carried out by Paterson Candy Ltd. The approach has been to use dye tests and velocity measurement to validate parallel investigations involving FEA. Much of this work is being carried out in tanks with polycarbonate sides measuring 3.2m (long) × 1.6m (wide) × 3.0m (maximum water depth). The tank, which is fitted with a counter-current recycle system, models a full-scale, two-inlet section of a COCODAFF® unit. In the current series of trials the inlets are baffled cones. These cones are constructed of perspex in order to facilitate the viewing of the dye distribution tests. Velocity measurements have also been made in the tank using an electromagnetic velocity meter. Velocities at the exit of a baffled cone are presented in Table 2.

The COCODAFF® process has a small footprint area, and can be rapidly switched to and from direct filtration mode.

Dye tracer tests, flow velocity tests, and FEA can assist in optimising the design of DAF and COCODAFF® processes.

References