Using lessons learned and advanced methods to design a 1,500 Ml/day DAF water treatment plant

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Abstract: The paper describes the method that led to the design of the 1,500 Ml/day dissolved air flotation (DAF) water treatment plant for Boston's water supply. In particular, the topics of flocculation techniques, floated solids removal and DAF recycle as they relate to very large capacity plant design are covered in detail. The use of mathematical models, including computational fluid dynamics (CFD) software, to refine the design is described.

Keywords: Drinking water treatment; dissolved air flotation; DAF; design; large capacity; mathematical models

Introduction

As part of an overall system upgrade, the Massachusetts Water Resources Authority (MWRA) is investigating filtration and non-filtration options for treating water from the Wachusett Reservoir. The MWRA provides drinking water to approximately 2 million people in metropolitan Boston, MA.

The 1,533 Ml/day (405 USmgd) Walnut Hill Water Treatment Plant that has been designed for the MWRA includes: a pre-treatment chemical facility; rapid mixing; flocculation; flotation; ozonation; granular activated carbon filtration; a post-treatment chemical facility; and two 95,000 m³ (25 million US gallons) on-site storage tanks. Also included in the treatment plant is a facility for the treatment of waste backwash water and floated solids. This “filtration” alternative design is complete. An “ozone-only” design has also been prepared as a non-filtration alternative. Site work is currently under way for the facilities that are common to both alternatives. The MWRA prefers to build the less expensive ozone-only alternative. The US Environmental Protection Agency (EPA) insisted that MWRA meet the provisions of the Surface Water Treatment Act and build a filtration plant. In a recent court case between EPA and MWRA, the federal court found for the MWRA.

As part of the preliminary design, a team of engineers visited DAF plants in England, Scotland and Sweden to gather information on the best technologies available and to interview plant personnel to determine the operability of large-scale plants (Crossley, 1996). Of particular interest was the DAF recycle systems that were used at each plant visited, including the saturation system (packed-tower or eductors) and the distribution system (fixed nozzles or valves). The visits also allowed an evaluation of methods used to remove floated solids.

The DAF design was refined by the use of mathematical models, including computational fluid dynamics (CFD) software.

Surge prevention and flow splitting

Water flows from the Wachusett Reservoir to the treatment plant approximately 13 km (8 miles) through the pressurized Cosgrove Tunnel. Another inlet is being provided for connection from the disused gravity Wachusett Aqueduct when it is pressurized in the future. Both transmission mains terminate at an inlet chamber attached to the surge tank.
The surge tank is located along the full length of the center section of the DAF building. The purpose of the tank is to accommodate a surge up to 190 Ml/d (50 USmgd) for 12 minutes in addition to the normal plant flow. An overflow weir directs the flow to the Wachusett Aqueduct if a surge exceeds this volume. Flow out of the surge tank to the four DAF process trains is conveyed in four pipelines. Each is fitted with a flow meter and control valve to divide the flow in proportion to the number of DAF tanks in service in each process train.

Mixing of chemicals
Effective mixing of pre-conditioning chemicals is essential to the DAF process. Each of the four process trains has three flash mixing stations arranged in series. Two of the three mixing stations will be equipped; the middle station will be provided for future use, but not equipped.

The mixing stations are designed to enable a variety of chemicals to be added: sodium hydroxide, aluminium sulfate, polyaluminium chloride (PACl), and coagulant aid polymer. Ferric coagulants can also be dosed should this be required in the future. Sodium hypochlorite will be used intermittently to disinfect the surge tank, mixing trains and DAF tanks. PACl is proposed as the primary coagulant, with aluminium sulfate, in combination with sodium hydroxide, as an alternate. Equipment to dose these chemicals is located on top of the surge tank. Each mixer has a variable frequency drive (VFD), so that different mixing conditions can be achieved using common equipment.

There is a hydraulic detention time (HDT) of 1.5 minutes at maximum plant flow between the addition of the sodium hydroxide and the coagulant, which allows the pH to stabilize after the dispersion of the sodium hydroxide.

Flocculation
During the extensive demonstration plant tests carried out by the MWRA during 1994 and 1995, the optimum flocculation residence time was found to be 10 minutes and good turbidity removal was found at a DAF loading rate of more than 20 m/h (8 gpm/ft²). Figure 1 shows the overall plan and elevation of the combined flocculation and DAF tanks.

Mixed water passes to the inlet channel feeding a bank of six flocculation/DAF tanks. The dimensions of the flocculation basins were set to match the width of the flotation tank.
and to share the same base slab elevation. Four individual compartments are arranged to give “square-on-plan” view, thereby ensuring hydraulic similarity.

It had been noted during the European visits that certain configurations of flocculation tanks gave rise to short-circuiting and, on occasions, flow reversal. Computational Fluid Dynamics (CFD) software was used to model and study the flow patterns from the inlet channel to the entry to the DAF tank. Single-phase CFD models were developed to optimize the flow paths through the rapid mix tanks, the flocculation and flotation tanks.

Good distribution of flow into and out of each flocculation compartment is very important. Flow through the inlet gate has its energy broken against a wall and the gate is located in the center to ensure hydraulic similarity. Water flows upwards and through two submerged, long and narrow distribution openings feeding the first stage of flocculation. The two flocculation stages are baffled in the middle to segregate the flocculation impellers. The size and position of the transfer openings was optimized using CFD to ensure equal flow through each of the two stages. Vertical baffles were added in the last compartment of each flocculation stage to prevent rotational energy being transferred into the final channel. These baffles dramatically improved the flow distribution into the DAF zone.

Each flocculation compartment is provided with a vertically mounted impeller. A variable frequency drive (VFD) allows rotational speed of the impeller to accommodate varying water conditions and to optimize floc size. Vertical turbine flocculators were selected for reliability and effectiveness compared to horizontal or vertical gate-type flocculators. Horizontal gate flocculators tend to suffer from shaft and bearing failure. They also require frequent attention to the drive chain and wheels due to wear. Vertical gate flocculators usually have no underwater bearings, but tend to impart a vigorous rotation to the flow, which can carry through into the DAF zone and affect the stability of the float.

**Flotation**

Extensive CFD studies were carried out to optimize the flow paths within the DAF tanks. These studies used two phases (air bubbles and water) and were performed with three-dimensional models (Crossley, 1999). Three-dimensional models, although more difficult to solve, result in better prediction of performance. Two-dimensional CFD models can give
misleading results owing to simplifications that have to be made to the inlet and outlet arrangements. Three-dimensional models are more suitable when the velocity magnitude of the vertical flow component is of the same magnitude as the horizontal velocity component.

For effective performance flow from the flocculation zone must be evenly introduced into the flotation zone. Flow into the flotation zone is through eight tapered ducts. The DAF recycle water is injected approximately halfway down the length of the duct. This ensures intimate mixing between the DAF recycle and the flocculated water. The location of the control valves and injection point in a gallery above the ducts gives excellent access to the valves and fittings for maintenance. This concept was used as a result of the design team’s visit to the Sjolunda Waste Water Plant at Malmo, Sweden.

The roof of each duct slopes upward to ensure air is not trapped. As a result of CFD analysis, it was found that the ducts needed to taper outward in the horizontal plane at an included angle of approximately 10 degrees. This taper gives significant benefits to the flow distribution into the flotation zone. CFD modeling was also used to optimize the DAF recycle diffuser design to ensure that the recycle flow is evenly distributed in the duct.

Like the Malmo plant, power-operated globe control valves are used to control back-pressure on the saturators in preference to fixed orifices or needle valves mounted on manifolds. The use of manually controlled valves or fixed nozzles limits the design of recycle systems to a narrow range of recycle flows.

With the ability to continuously vary the recycle flow and saturator pressure with changes in plant flow, no excess recycle flow is required to ensure good process performance and operational cost efficiency. Using power operated globe valves to provide a constant back-pressure in the saturator results in optimum power consumption over the full operating range. The control valve trim has been specially selected to maximize microbubble generation.

The riser baffle into the flotation tank is vertical. Sloping the riser baffle can encourage back mixing and consequent short-circuiting within the microbubble/floc contact zone. The purpose of the riser section is to allow contact time between the microbubbles and the floc particles, and to direct the flow upward to the tank surface. The cross-flow velocity over the chamfered baffle is set relatively high to improve the bubble reach in the tank. It was found by CFD studies that chamfering the re-entrant edges of the flow path significantly reduced recirculation and short-circuiting in the contact zone.

Four effluent ducts are located along the base of each flotation tank. In the sidewalls of each duct are distribution orifices. The purpose of these ducts is to draw clarified water evenly from beneath the bubble zone in the upper part of the flotation tank. Orifices are located away from the inlet baffle wall to improve flow distribution within the tank. During the CFD studies, the location of the orifices and lateral position of the ducts was found to have a noticeable effect on the flow patterns in the tank.

An adjustable full-width outlet weir sets the operating water level in the flotation tanks. From the European visits, it was found that being able to see clarified water cascading over the outlet weir gave the operator confidence that the process was working well. To assist in the assessment of water clarity the top surface of the weir is tiled in checkerboard fashion.

The turbidity from each DAF tank is monitored to check that floated solids removal is being adequately carried out and to pinpoint any problems occurring with individual flotation cells. Bulk floated water turbidity, particle count, and pH are monitored. This information enables the optimization of coagulant dose and pH, which in turn minimizes chemical usage, gives longer filter runs, and reduces the load on the residuals handling facilities.

**Floated solids removal**

The European visits illustrated that removal of float from the surface of the flotation clarifiers can be achieved in a variety of ways, each having advantages and disadvantages.
Some plants used surface skimmers. The main advantage of using a surface skimmer is that the floated solids concentration is high, normally up to 3% by mass. This eliminates the need to thicken prior to disposal to a lagoon or to dewatering equipment, such as a centrifuge or membrane filter press. Most large treatment plants have facilities for the filter backwash waste recovery, and so high floated solids concentration is not such an advantage as first appears. There are several disadvantages in using surface skimmers. The main disadvantage is mechanical complexity, which increases capital cost and maintenance. Skimmers can cause “knock-down” of float, increasing effluent turbidity while the skimmer is operating. In addition, the float may be so viscous as to need water sprays to encourage it to flow to the storage tanks, defeating some of the advantages of having a skimmer. Cleaning the skimmer flights is required on a regular basis.

One plant visited by the design team used a rotating paddle wheel at the end of the DAF tank to remove the float. The paddle wheel relies on the elastic and cohesive properties of the float to “pull” it from the water surface. Although it is simpler than the surface skimmer, the paddle wheel shares its disadvantages.

The method that is most appropriate to large water treatment plants is float removal by hydraulic flooding, and this method was selected for the Walnut Hill project. The key benefits of hydraulic float removal are simplicity, low capital cost and ease of waste transportation.

Water level in the flotation basin is increased for a short period so that a small portion of the flow through the flotation tank carries over a weir and into a floated solids channel at the end of the tank. Two outlet weirs are placed in sequence. Under normal operating conditions the clarified water flows over the first (primary) weir and bypasses the second (secondary) weir by means of a gate. To remove floated solids, the gate is closed and the water now passes over the second and higher weir. The weir elevation is set so that most of the water flows out of the clarifier and between one tenth and one fourth of the influent cascades over the floated solids outlet weir. The resultant waste stream has a solids content of between 0.2 and 0.5% by mass, and is directed to a thickener for treatment. A mathematical model was developed to determine the relative weir elevations and predict the solids concentration at varying inlet flows and recycle rates. During the float removal process, water is gently sprayed onto the tank wall just above the float surface. The purpose of the spray is to provide a lubricating film of water between the concrete wall and the float, to break surface tension at the wall and assist in the floated solids removal process. It is important that the spray is not too vigorous or the float will be damaged and knocked down, creating turbidity carry-over.

Recycle system
The recycle system effectiveness is crucial to the success and economy of the DAF process. The Scandinavian approach to saturating water with air is to use an eductor to intimately mix the air and the recycle water, and pass the emulsion at a pressure of about 4 bar (60 psi) to a pressurized detention tank. Large bubbles separate in the tank, the level of water being controlled by the addition of air under pressure, and the smaller bubbles are driven into solution. Usually, for large treatment plants there is one detention tank for each flotation cell.

An alternative method is to use a packed tower saturator where water cascades over packing media while under pressure of 4 to 7.5 bar [60 to 100 psi]. The higher operating pressure enables more air to be driven into solution and the wetted surface area of the packing gives a very high mass transfer of air to water. For the same duty, packed tower saturators require fewer vessels and less equipment than the traditional detention tank approach. For the Walnut Hill project the packed tower arrangement was chosen because it is more efficient and more cost effective.
The recycle system is designed to provide over 11 g/m$^3$ of dissolved air in the flocculated influent at 18°C [65°F] water temperature. To drive the air into solution and produce a high air/water concentration requires a large wetted contact area and a high operating pressure in the saturator.

There are two independent recycle systems within the treatment plant, each supplying air-saturated water to two trains of six DAF tanks. Each system is centrally located so that pipework distances and pipe hydraulic losses are minimized. Low hydraulic losses result in less air coming out of solution in the distribution pipework, which maintains the overall efficiency of the recycle system. Four recycle pumps, one self-cleaning strainer (with bypass), four packed tower saturators, and three air compressors are provided for each recycle system. Redundancy is provided within each recycle system so that failure of one piece of equipment will not cause a treatment process malfunction.

Air compressors are the most vulnerable part of the recycle system and three per set are provided to reduce the risk of failure to a minimum. Screw compressors are used in preference to using oil-free reciprocating compressors, owing to the latter’s poor reliability and high maintenance requirements.

Within each compressed air system there are three compressors, two air receivers, two sets of three-stage filters and two sets of air dryers (refrigerant and desiccant). The air filters remove small particulates and absorb any hydrocarbon carryover from the compressors, while the dryers condition the air for the saturator outlet valves and recycle control valve positioners/actuators. Dual air lines are provided to give added redundancy.

Each recycle system has four vertical canned turbine pumps. This type of pump was selected to save space and to preclude any chance of the motors being flooded. Each of the pumps has a VFD, which, together with the DAF recycle control valves, gives step-less adjustment of recycle flow percentage to influent of between 6 and 11%.

One self-cleaning strainer is provided for each recycle system. The strainer is sized to remove particles greater than 400 µm [0.02 in] and prevents floc from fouling the saturator packing in the event of a process upset. Cleaning of the strainer is initiated on differential pressure build up or elapsed time.

The performance of the DAF saturators was optimized using a mathematical model that was based on a procedure published by Haarhoff and confirmed with full-scale tests by Valade (in progress). The optimization of the DAF recycle system for the Walnut Hill WTP is more comprehensively described in a paper by Valade et al. (1998).

Two banks of four saturators are provided, with one saturator redundant per group of four, enabling inspection of the vessel internals without a reduction in plant capacity. The saturators are rated for the closed-valve head of the recycle pumps, which avoids the need for a large pressure relief valve on the recycle pipeline.

The saturator outlet valve is a pneumatically-actuated spring-to-close butterfly valve that fails-safe in the event of a power failure, or closes if a low-low water level condition occurs in the saturator. This prevents air blowing down the recycle pipes, which can cause massive disruption to the DAF process. A local panel is provided next to each pneumatically actuated valve in order to open and close the valve under manual control. A sight gauge and an analogue level transmitter monitor the water level in the saturator. Both instruments are fitted in stilling wells mounted on the side of the saturator. These features have been found to be essential during start up and normal maintenance. Pressure in the saturator is monitored and the signal used to control the position of the DAF recycle control valves that create the micro-bubbles. From each group of four saturators, a discharge manifold splits into lines feeding two trains of six DAF tanks. Each DAF tank recycle feed line has a motorized butterfly isolation valve and magnetic flow meter to monitor the recycle flow and trim the set point of that tank’s recycle control valves. Eight pneumatically actuated and
positioned recycle control valves are fed from a common manifold at each DAF tank. The DAF recycle flow is injected into the eight transfer ducts between the flocculation and flotation tanks by means of a simple diffuser.

All the wetted parts of the recycle system are either 316 stainless steel or plastic construction so as to avoid corrosion from the highly aggressive water. It was clear from the European visits that uPVC and polypropylene pipe was not reliable under the high pressure, shock load conditions experienced occasionally in recycle systems. Consequently, all recycle pipework is fabricated from 316 stainless steel. The saturator vessels are manufactured from carbon steel, which is shot blasted and epoxy coated. The internal epoxy coating is spark-tested for holidays and inclusions.

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**References**
