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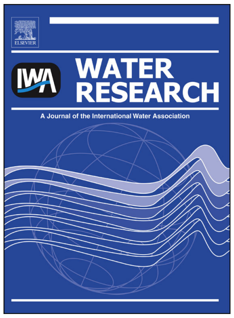

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Low energy ballasted flotation

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Abstract

A novel process which involves the replacement or supplementation of bubbles in the dissolved air flotation process with low density beads is presented. The work comprised a series of bench scale flotation trials treating three commonly encountered algal species (*Microcystis*, *Melosira* and *Chlorella*) that were removed in a flotation cell configured as either: conventional dissolved air flotation (DAF); ballasted flotation using low density 70 micron glass beads with a density of 100 kg.m^{-3}; or a hybrid process of ballasted flotation combined with conventional DAF. Results indicated that the bead only system was capable of achieving better residual turbidity than standard DAF at bead concentrations of 500 mg.L^{-1}. Addition of beads in combination with standard DAF reduced turbidity further to even lower residual turbidity levels. Algae removal was improved when glass beads were dosed, but removal was dependent on algal species. *Microcystis* was removed by 97% for bead only systems and this removal did not change significantly with the addition of air bubbles. *Melosira* was the next best removed algae with bead only dosed systems giving similar removals to that achieved by standard DAF using a 10% air recycle ratio (81 and 76% removal respectively). *Chlorella* was the least well removed algae by bead only systems (63% removal). However, removal was rapidly improved to 86% by the addition of air bubbles using only a 2% recycle ratio. Energy estimations suggested that at least a 50% energy reduction could be achieved using the process offering a potential route for future development of low energy separation processes for algae removal.

Keywords: Algae, Bubbleless, Dissolved air flotation, Energy,

Introduction

Dissolved air flotation (DAF) is an established solid-liquid separation technology process in water treatment for removal of low density floc including those containing algae or dominated by natural organic matter (NOM) and in low temperature countries (Schofield, 2001). In the DAF process, floc formed in preceding coagulation and flocculation stages are separated from water by the attachment of bubbles onto the floc. The bubble-floc aggregate becomes less dense than water and therefore floats to the top in a flotation tank forming a sludge blanket. Clarified water exits the tank from beneath the float, whilst the sludge blanket is periodically removed from the top. A key component in any DAF system is the generation of micro-bubbles by saturating air with water. During saturation, between 5-15% of the clarified flow is recycled and mixed with air supplied by a compressor. The air-water mixture is then pressurised to between 400-650 kPa to dissolve the air into the water. The pressurised air-water mix is then introduced into the flotation tank at atmospheric pressure through nozzles. As a result of the release of the pressure drop, the excess air precipitates out in the form of bubbles that are typically between 40-100 μm (AWWA, 1997). A benefit of the system is in its ability to adjust to water quality and solid concentration changes by altering the number of bubbles released by changing the recycle ratio enabling changes in the particle loading to be effectively matched by addition of more or less air bubbles.

As well as being a large capital cost, the saturator and recycling systems account for approximately 50% of the operating costs of a DAF system (Haarhoff and Rykaart, 1995). This is principally from the electrical energy consumption of around 0.3 kWh.m^{-3} of treated water for the operation of the compressor of the saturator and the pumping of the recycling system (Viitasaari *et al*., 1995). Consequently significant saving could be made if the need for bubble generation could be removed. A bubbleless system may be achieved using the concept of ballasted flotation. In ballasted flotation, a low density material is incorporated into the floc to give the aggregate an overall density less than that of water so that the particle floats without the need for bubbles to be attached. Low density materials that could be used include a range of commercially available hollow spheres composed of latex or glass or solid particles that float in water (composed of a material such as polystyrene). This concept is described in two patents: WO/2006/008474 and US Patent 6890431 but there is no other published research on the process. Analogy of the ballasted flotation concept can be made with sedimentation systems where floc densities are increased by adding ballasting agents of high density. Examples of ballasting agents include activated carbon, recycled sludge (Landon *et al*., 2006), magnetic particles (Booker *et al*., 1996) and sand (Plum *et al*. 1998). The latter is perhaps the most commonly adopted version under the trade name Actiflo® and is used for a range of applications including tertiary treatment of sewage, intermittent discharges and potable water treatment (Guibelin *et al*., 1994; Imasuen *et al*., 2004). Similarly, the advantage of using a low density ballasting agent could have the equivalent effect of enhancing flotation (in combination with bubbles) or replacing the need for bubbles entirely resulting in a significant energy reduction for the flotation process. Ballasted flotation could be used in all applications where standard DAF is currently used, such as treatment of waters that are dominated by algae or NOM. The work presented here investigates the practical feasibility of ballasted flotation by examining the efficacy of implementing recyclable low density beads to replace the bubbles used in DAF in bench scale jar test trials for removal of particles from water spiked with algae.

Materials and Methods

A series of bench scale jar tests was carried out to determine the feasibility of using low density glass beads for flotation of floc dominated by algae. Tests were carried out in one of two formats: 1) **Traditional DAF** and 2) **Ballasted flotation.**

Traditional DAF: Jar tests were carried out using a model DBT6 DAF batch jar tester (EC Engineering, Canada). The DAF jar tester operates in a similar way to a standard jar tester during the floc formation stage using 1 L samples of water contained in 1 L square beakers. Water was rapid mixed for 1 minute at 200 rpm followed by a slow stir period at 30 rpm for 15 minutes. For flotation of floc, the DAF jar tester adds pressurised water saturated with air into the jar through diffusers enabling bubbles to form that can attach to the flocs and float them to the surface of the jar. The amount of air saturated water added into the jar was varied from 0-10% of the 1 L sample in the jar (referred to as the recycle ratio). The 0% recycle ratio represented a sedimentation system because no air bubbles were dosed into the system to enable flotation to take place. Water was sampled from a sampling tap a third of the way up the jar after 10 minutes of flotation. For each jar test, samples were analysed for turbidity using a Hach 2100 turbidimeter after 10 minutes of flotation following the addition of air bubbles into the jar tester.

The water tested was from a lowland reservoir from the east of the UK. The water had a turbidity of 6.5 ± 1.7 NTU. Water was coagulated using ferric sulphate (Ferripol XL, EA West) at a dose of 3.5 $mg.L^{-1}$ as Fe at pH 5.5 (a pre-determined optimum for this water). Initial testing was carried out on the raw water. Subsequent tests to determine the effectiveness of low density beads on algae removal were carried out by separately spiking raw waters with three different algae species: *Microcystis* (cyanobacteria); *Melosira* (diatomaceous algae); *Chlorella* (green algae). Algae were cultured in nutrient rich Jaworski medium in sterile beakers at 15 $^{\circ}$C in a continuous light environment. The water was spiked with algae to simulate bloom concentrations at between 0.5-1.0 x 10^6 cells.L^{-1}. Algae were enumerated using a Neubauer hemocytometer before and after flotation. The number of fields of view required to count 100 individual algal cells for a specific magnification was measured and equated to the volume of water contained in the hemocytometer for each field of view.

Ballasted flotation: Low density glass beads from Trelleborg, Emerson and Cuming Inc (Mansfield, USA) were used in flotation tests as provided by the manufacturer. Manufacturer information reported the beads having a median size of 70 μm and a density of 100 kg.m^{-3}. The beads were dosed into the water before the coagulant was added and mixed briefly to disperse in the jar at concentrations between 100-900 mg.L^{-1}. The jar test was then carried out as described before for recycle ratios between 0-10%. In this case the 0% recycle ratio was a flotation test because the beads in the floc reduced the density of the aggregate to below that of the water. To determine whether the beads could be effectively re-used after coagulation, the bead-floc float was broken up by rapidly mixing on the jar tester to separate the two at 200 rpm for 1 minute. The mixing was stopped and the beads that floated to the top of the jar after 10 minutes were collected and re-used in a subsequent jar test using the previously described coagulation procedure. This was repeated five times.

The particle size distribution (PSD) of the beads used in this work was validated using a Malvern Mastersizer (Malvern Instruments, UK). Beads were added into 1 L of de-ionised (DI) water in a 1 L square beaker at a concentration of 300 mg.L^{-1}. The beads were mixed on a jar tester at 200 rpm and pumped through the optical unit of the Mastersizer and back into the jar. An average of three measurements was used to provide the final PSD. The size of the flocs formed on the jar tester with and without glass bead addition were also measured using the Mastersizer instrument. The suspension was monitored by drawing water through the optical unit of the Mastersizer and back into the jar by a peristaltic pump on the return tube using 5 mm internal diameter peristaltic pump tubing at a flow rate of 1.5 L.hr^{-1}. Size measurements were taken every minute for the duration of the jar test and logged onto a PC.

Modelling floc sedimentation and rise rates was carried out using Stokes' law. There is some uncertainty in using Stokes' law for flocs due to their porous and irregular structure but the application provides a useful relative comparison and is widespread in floc analysis (Bache *et al*., 1991; Gregory, 1997; Tang *et al*., 2002). In this analysis, floc were assumed to be spheres consisting of i) flocculated matter (algae and coagulant precipitates) and ii) glass beads with a diameter of 70 μm. The density of the flocculated matter was modelled between 1010-1060 kg.m^{-3}. These density ranges were selected based on literature values for different types of floc (1038-1065 kg.m^{3} for activated sludge flocs (Sears *et al*., 2006); ferric hydroxide floc density estimated 1050 kg.m^{-3} (Bastamante *et al*., 2001); algae floc modelled as 1020 kg.m^{-3} (Haarhoff and Edzwald, 2001)). Glass bead density was taken as 100 kg.m^{-3} from manufacturer data.

Results

The performance of the system was dependent on both the bead concentration and the equivalent recycle ratio applied (Figure 1). In the case of traditional DAF, the residual turbidity ranged from 1.7 to 4.2 NTU as the recycle ratio decreased from 10 to 2% (0 mg/L bead concentration, Figure 1). Addition of beads to the system resulted in either no change or a slight decrease in turbidity except at high bead doses and low recycle ratios (Figure 1). For instance, at a recycle ratio of 6% the residual turbidity with no beads was 2.6 NTU and ranged between 1.4 and 2.9 NTU for bead concentration between 100 and 900 mg.L^{-1}. For ballasted flotation, the application of beads without the use of any bubbles (0% recycle ratio) resulted in residual turbidities between 2.4 NTU at 600 mg.L^{-1}

and 5 NTU at 200 mg.L^{-1} indicating that the use of beads and no bubbles approached the performance of traditional DAF (Figure 1). Closer inspection of the residual water revealed beads remained in the water which reflected a distribution of properties observed in the beads and the fact that no pre-conditioning was conducted. This observation was confirmed by recovering the floated beads and reusing them on consecutive application (Figure 2). After the first use of the beads at 500 mg.L^{-1}, the residual turbidity was 3.5 NTU, this was reduced to 1 NTU after the fifth use of the same beads. This was below that achieved for a system at 10% recycle ratio without any beads added (1.7 NTU) showing that the beads could be effectively recycled and that, in fact, the bead system was capable of working better than traditional DAF after the beads had been used three times or more. A 41 % improvement in residual turbidity was observed using the bubbleless bead system (ballasted flotation, 0% recycle) compared to traditional DAF after five uses of the bead (Figure 2). The observed improvement with multiple uses reflects the removal of non floating beads due to imperfections in manufacture that lead to thicker walls of the spheres than intended, increasing the density of the beads. In addition, breakage of the spheres can also occur. Manufacturer data indicated that 1% of the beads by volume may be expected to be failures that do not float. Given that glass typically has a density of 2,200 kg.m^{-3} or above (Koike and Tomozawa, 2007), non-floating beads will have a significant impact on overall floc density. However, removal of such beads during a pre-conditioning process effectively negates the problem. In this case, pre-conditioning was achieved through the multiple re-use of the same beads and resulted in a system that generated a lower residual turbidity than traditional DAF.

Comparison of the efficacy of the ballasted flotation in relation to differing algal species indicated a small difference in performance depending on the specific species tested. The bubbleless bead process (0% recycle) was seen to be most effective for flotation of the algae *Microcystis* resulting in 97% removal. Removal did not change significantly with the addition of bubbles, fluctuating between 92 and 96%. Conversely, for systems with no beads added, removal increased from 16 to 78% removal with increasing recycle ratio from 0 to 10 %. *Melosira* was the next easiest algae to remove increasing from 81% removal to 96% with increasing recycle ratio for systems with bead dosing. Of note, it was evident that removal of *Melosira* for a bead dosed system and no air bubbles resulted in slightly better removal than for no beads at 10% recycle ratio with values of 81 and 76% respectively. *Chlorella* was the most poorly removed algae when no bubbles were added for bead dosed systems at 63% removal, however the addition of a small number of bubbles (2% recycle ratio) increased removal up to 86%. This removal was significantly above the level seen for non-bead dosed systems at the highest recycle ratio of 10% which produced 70% removal.

The range of algae removal observed during traditional DAF operation was in a similar range to that seen previously in operational DAF systems of between 80-98% (Markham *et al*., 1997). The differences in removal for different algae reflects the differences in structure between species. All of the algae floc showed poor removal when clarification was by sedimentation. This was particularly the case for *Chlorella* and *Microcystis* which were only removed by <20% in a sedimentation system. Both of these algae exist as small single celled spheres between 2-10 μm (Henderson *et al*., 2008). *Melosira* is a diatom that forms much larger long chain colonies. Diatoms also contain silica in their cell walls which has a high density (2200 kg.m^{-3}). The combined effect of increased size and density explains why *Melosira* was the best removed algae by sedimentation. Regardless of this, algae flocs were much better removed by flotation processes, a conclusion reached by other researchers (Teixeira and Rosa, 2006). *Microcystis*, a cyanobacteria, is a very low density algae because it has a gas vacuole within the cell structure which enables the algae to control its buoyancy in the water column. This makes removal of floc containing *Microcystis* particularly amenable to removal by flotation. However, for conventional DAF, these algae floc were poorly removed until 6-10% recycle ratios. With glass beads, *Microcystis* floc were very well removed by flotation without the need for any bubbles (0% recycle). For the algae without a vacuole (*Melosira* and *Chlorella*), the very highest removals were seen involving a combination of low density beads and air bubbles. This indicates that a combined effect of algae structure, morphology and density has a significant impact on removal efficiency by coagulation and clarification, a conclusion that is in agreement with numerous other studies on particle flotation (Valade *et al*., 1996; Henderson *et al*., 2008).

The presence of beads in the algae coagulation systems aided the removal of algae for all of the recycle ratios investigated and the different algae species. In addition to improved flotation, the presence of small spheres may have increased the incorporation of algae into the floc that resulted in fewer non-flocculated algae in the jar test. A high concentration of small particles provides nucleation points for coagulant precipitates to form around and encourage floc development and can promote enmeshment of algae within the floc matrix. The addition of kaolinite and activated silica has been added for this purpose to improve natural organic matter removal (Gregor *et al*., 1997).

The average size of the floc for systems dosed with and without glass beads was significantly different for the two systems (Figure 4a and b). Non-bead dosed systems grew to a median floc size of 600 μm, reaching this size after 7 minutes of the jar test. For systems dosed with beads, the flocs grew to a size that reached a maximum of 260 μm after 4 minutes of the jar test, but stabilised at 185 μm. As can be seen in the inset image in Figure 4, numerous beads were observed to be incorporated into the algae-coagulant floc with over 25 beads in the floc with a diameter of 500 μm. Given that the maximum floc size was reached significantly before the end of the 15 minute flocculation time for both systems in the jar test experiments, shorter flocculation times are advocated. This is in agreement with other research suggesting that flocculation periods of 5-10 minutes are recommended for DAF (Edzwald, 1995).

The reduced floc size observed was an indication of reduced floc strength for floc containing beads given that the steady state floc size has been shown to be an indicator of floc strength (Yukselen and Gregory, 2004; Jarvis *et al.*, 2006). However, although there was a difference in the average floc size for systems with and without beads added, it should be noted that in conventional DAF, floc are exposed to high energy when they are mixed with bubbles which breaks up the floc. The shear rates in DAF have been estimated to be between 1000-7600 s^{-1} (Masschelein, 1992; Fukishi *et al.*, 1995). It has been shown that the maximum floc size at shear rates of 1000 s^{-1} were between 30-281 μm which were formed from floc sizes of 600-1200 μm at 10 s^{-1} showing that floc size was significantly reduced under the conditions prevalent in DAF (Bache and Rasool, 2001). Flocs formed in a bead dosed system and separated with no air bubbles added would not be broken up because they would not be exposed to these high shear rates, enabling floc to maintain their size as formed in the flocculator. The importance of this relates to the breakage products formed, which includes the formation of floc around 1 μm in diameter. These sized particles cause significant operational problems because they are poorly removed in downstream filtration processes. Limiting exposure of flocs to high shear rates in flotation, as well as in the preceding coagulation and flocculation stage, is particularly important for systems containing algae that may release toxins (such as *Microcystis*) under high shear stresses (Edzwald and Wingler, 1990). The proposed ballasted flocculation process would eliminate the need for the high shear rates used today in most operational DAF plants.

One consequence of dosing glass beads into the system will be an initial increase in sludge volume. However, because the beads will be removed from the sludge and re-used, the volumes of sludge to be treated and disposed of will be the same as that for a conventional DAF system.

The use of rise velocity modelling to establish the sensitivity with which bead properties influenced performance indicated that the density of the coagulated material had little impact on settling and rise rates at the mean floc size observed in the current study of around 200 μm (Figure 5a). The theoretical settling rate of the flocs with no beads varied from 0.08 m.h^{-1} and 0.47 m.h^{-1} for the lowest and highest floc densities used. A floc containing 10 beads had a theoretical rise velocity of 2.8-3.0 m.h^{-1} with around 43% of the total floc volume contributed from the bead. A floc containing 20 beads had a rise velocity of 6.0-6.1 m.h^{-1} but would only contain 15% floc matter whilst above 23 beads, the volume of the beads would exceed the volume of the complete 200 μm floc. As a comparison to these modelled values, rise velocities for bubble-floc aggregates have been measured as 3 m.h^{-1} for ferric hydroxide-algae floc (Vlaski *et al*., 1997) for floc with an average size of 15-20 μm. The rise velocities of activated sludge flocs were captured between 1.8 and 37.8 m.h^{-1} with two thirds of the flocs measured having rise rates between 5 and 15 m.h^{-1} (Ljunggren *et al*., 2004).

The simple calculations have demonstrated that it is possible for floc containing beads to have rise velocities similar to the range observed in other studies. Given the similar or better turbidity removals observed for ballasted flotation (with no bubbles) when compared with conventional DAF, it would be expected that the performance observed in jar tests would be translated to continuous systems. The key is to ensure that enough beads are incorporated into the floc to enable high rates of flotation and promote the formation of large floc. For a 200 μm floc, the average floc size seen in this work, this would require between 10-20 beads to be contained in the floc structure. If larger floc can be formed and maintained it would be possible to generate flocs with theoretical rise rates of >40 m.h^{-1} for floc >500 μm containing over 300 glass beads (Figure 5b).

Discussion

This bench-scale study has shown that using floating beads potentially offers an alternative means of separating floc from treated water giving similar levels of residual turbidity to conventional flotation systems with air bubbles. In principle, any coagulated material (algae, activated sludge, NOM or minerals) could be floated from the system so long as enough beads are incorporated into the floc aggregate to significantly reduce the density of the floc below that of the water. A conceptual flow diagram of a how a ballasted flotation system may be implemented at full scale shows the replacement of the saturator with a hydrocylone to recover beads and two additional pumps to transport either recycled or fresh beads into the flocculation tanks (Figure 6). The reduction in energy usage by removing the need for the saturator has two benefits: a direct saving in money and a reduction in carbon footprint. Evaluation of the impact of such a system requires accurate information about the energy usage of individual components within water works which is currently not commonly available. Estimates for the energy used for the saturation system of a typical DAF plant range between 0.1 and 0.3 kWh.m^{-3} (Viitasari *et al.*, 1995) and this compares to around 0.003-0.02 kWh.m^{-3} for a typical hydrocylone (Vion, 2000). Even after the inclusion of pumps, the ballasted flotation process should still enable at least a 50% reduction in energy to be generated when compared with traditional DAF. To illustrate the potential impact of this, the energy saving at a standard water treatment works operating at 50 Ml.d^{-1} would be 1,825,000 kWh.year^{-1} if it switched from traditional DAF to the ballasted flotation process (assuming a saturator operating at 0.2 kWh.m^{-3} and a 50% energy reduction when using floating beads with hydrocyclones and additional pumping). This equates to 196 tCO$_2$e.year or an annual cost saving of £127,750.

The current study was focussed on evaluating the potential of utilising beads to ballast a flotation process at bench scale. The positive results presented then raise questions about its implementation, most importantly: (1) what is the risk of beads entering the final water and (2) how effectively can the beads be recycled and at what loss rate. The presented work provides some evidence towards the first question: First use of the beads resulted in high numbers of residual beads but subsequent use reduced this number significantly demonstrating that appropriate pre-conditioning is essential and effectively removes the problem. Further, given the bead size of 100 μm, any beads carried over with the clarified water will be captured within the downstream filtration processes (Henderson *et al.*, 2008). Consequently, the possibility of bead carryover into the product water is very low. The second question remains crucial. Whilst batch recovery of the beads through high speed mixing within a jar tester worked effectively, translation into a continuous process is important as the energy required to operate the plant and the bead loss rate will define the overall economics of the process. In addition, whilst it is not expected, further work is required to clearly demonstrate that ballasted flotation will not increase cell lysis and increase the release of algogenic organic material, particularly in relation to toxic compounds from *Cyanobacteria*. However, these results have demonstrated that the ballasted flotation process appears to be very effective technology for algae removal and could have much wider application in water, wastewater and industrial solid-liquid separation processes.

Conclusions

Application of low density glass beads as a flotation ballasting agent effectively removes the need for dissolved air in the flotation process. In the case of algae the efficacy of the ballasting agent was related to the characteristics of the algae and was most effective for *Microcystis* species. Floc diagnostics revealed that ballasted flocs were smaller than those formed during the coagulation of algae. However, in practice these floc will not be exposed to the higher shear rates of traditional DAF because of the removal of the dissolved air injection stage. Floc breakage is therefore minimised, ensuring that the concentration of residual turbidity in the clarified water is low and composed of larger floc that will be more amenable to removal by filtration. Overall the use of beads provides a low energy alternative to traditional DAF which can meet or exceed performance and provide in-process and downstream benefits through extended filter run times.

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Figure 1. Residual turbidity for increasing bead concentration at different DAF recycle ratios after 10 minutes flotation. The coagulation conditions were 3.5 mg.L^{-1} Fe at pH 5.5. Raw water turbidity 6.5 ± 1.7 NTU spiked with algae at concentrations between 0.5-1.0 x 10^{6} cells.L^{-1}.

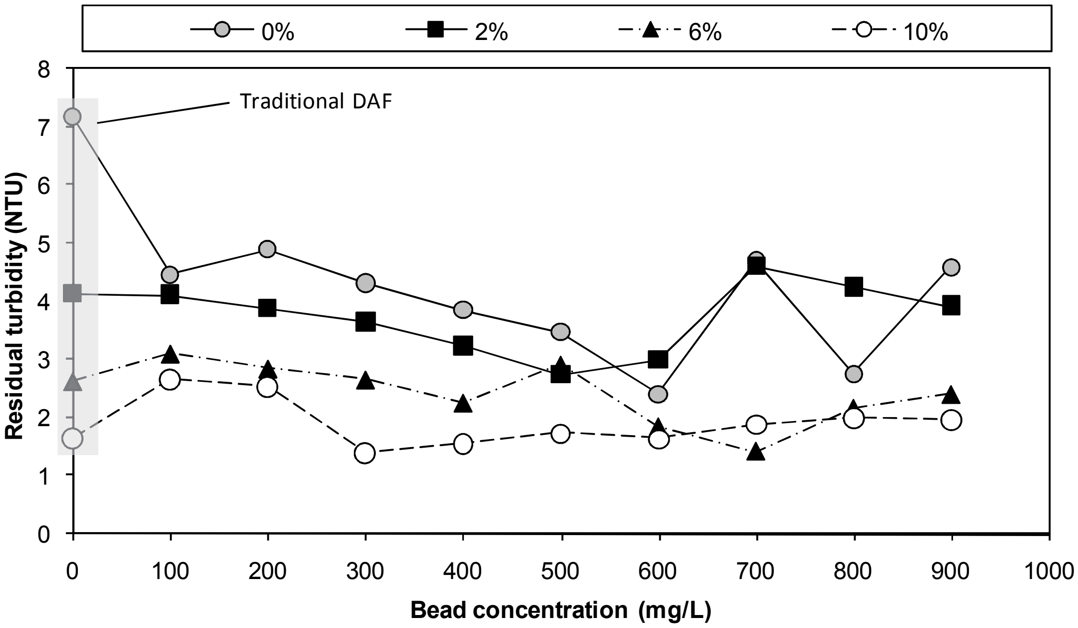
Figure 2. The residual turbidity of treated reservoir water after treatment with beads. The beads were dosed at a concentration of 500 mg.L^{-1}. No air bubbles were added into the system (0% recycle ratio). Coagulation conditions were 3.5 mg.L^{-1} Fe at pH 5.5. Raw water turbidity was 6.5 ± 1.7 NTU spiked with algae at concentrations between 0.5-1.0 x 10^{6} cells.L^{-1}.

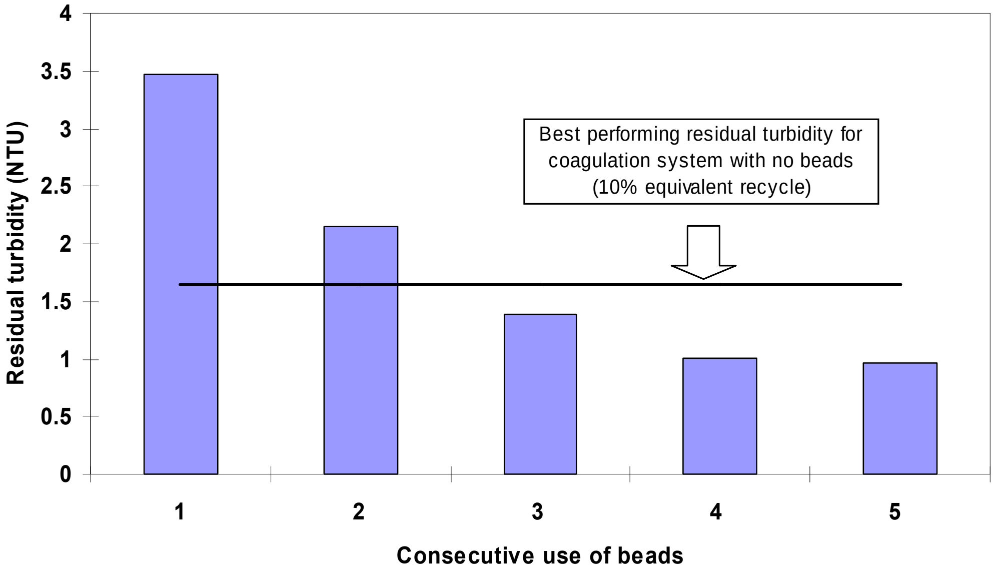
Figure 3. Percentage removal of algae (from microscope counting) for *Microcystis*, *Melosira* and *Chlorella* algae species for increasing recycle ratios for systems with and without beads. Beads were dosed at a concentration of 300 mg.L^{-1}. The coagulation conditions were 3.5 mg.L^{-1} Fe at pH 5.5. Raw water turbidity was 6.5 ± 1.7 NTU spiked with algae at concentrations between 0.5-1.0 x 10^{6} cells.L^{-1}.

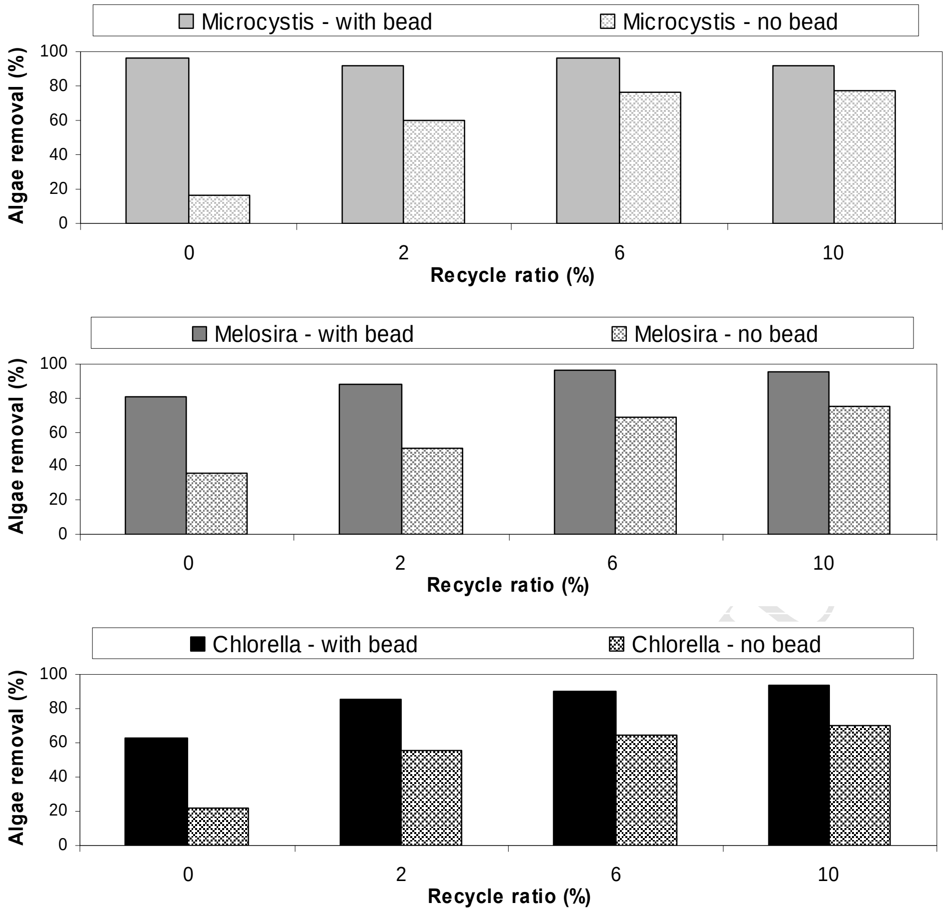
Figure 4a and b. Floc growth & PSD for coagulated systems with and without beads for water spiked with *Microcystis*. Bead concentration was 500 mg.L^{-1} and the coagulation conditions were 3.5 mg.L^{-1} as Fe at pH 5.5. Raw water turbidity was 6.5 ± 1.7 NTU spiked with algae at concentrations between 0.5-1.0 x 10^{6} cells.L^{-1}.

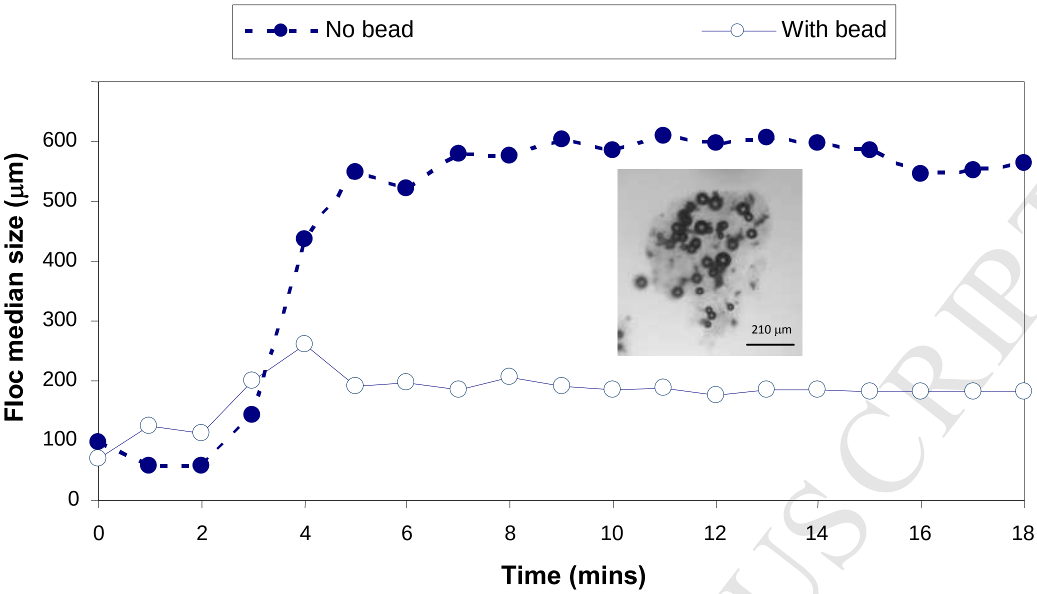
Figure 5. The change in floc settling/rise rates dependent on the number of beads in the floc and variable density (a) and floc size (b). a) Impact of the density of coagulated material (kg.m^{-3}) on settling/rise rates (SI 100 beads, floc size 200 μm), b) Impact of floc size on settling/rise rates (floc size 200 μm, density of coagulated matter 1020 kg.m^{-3}).

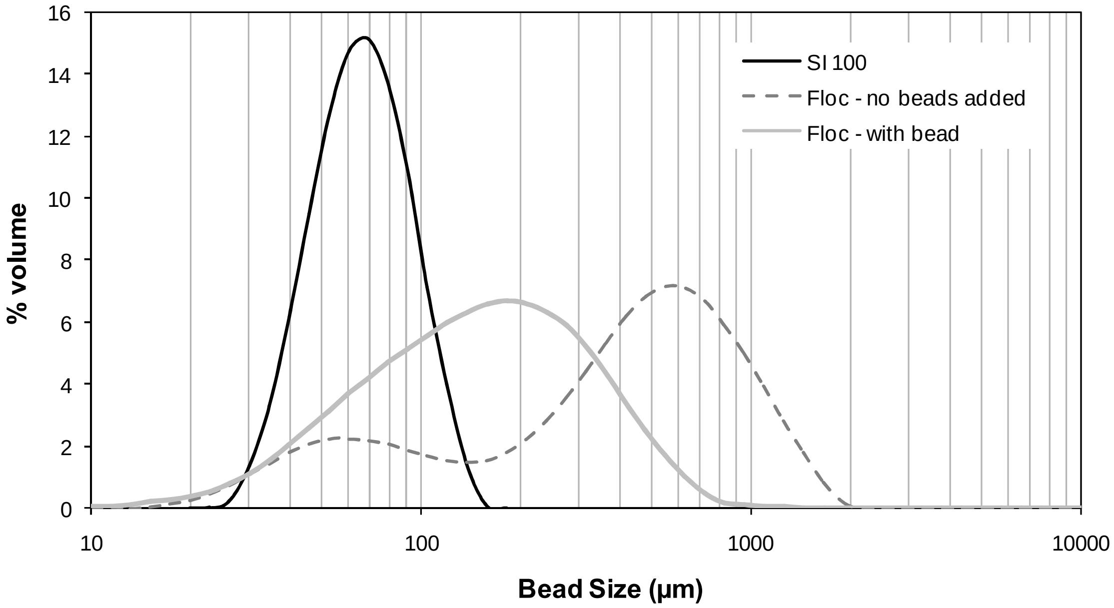
Figure 6. Conceptual schematic of the bubbleless flotation system.

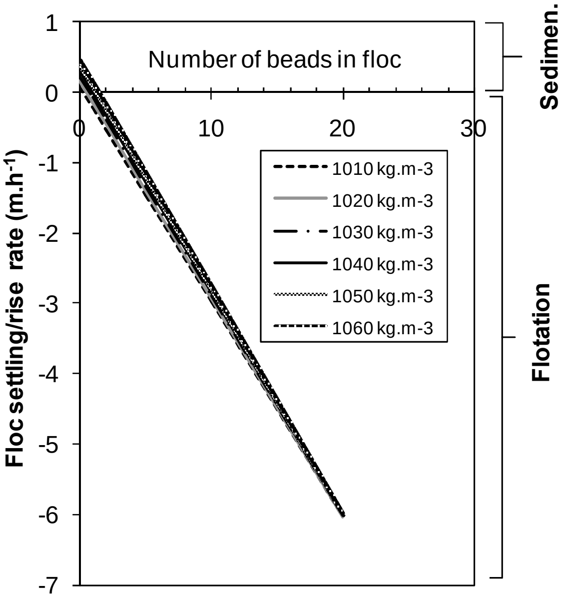

0%
2%
6%
10%
Traditional DAF
Residual turbidity (NTU)
Bead concentration (mg/L)
0
1
2
3
4
5
6
7
8
0
100
200
300
400
500
600
700
800
900
1000

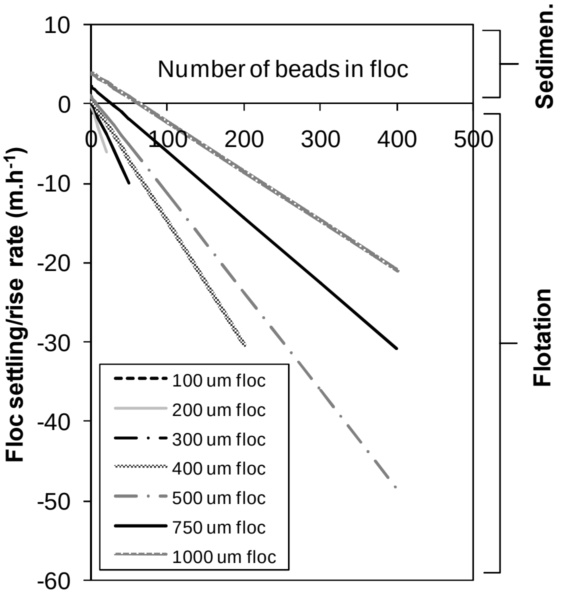

Residual turbidity (NTU)
0
0.5
1
1.5
2
2.5
3
3.5
4
Best performing residual turbidity for coagulation system with no beads (10% equivalent recycle)
1
2
3
4
5
Consecutive use of beads

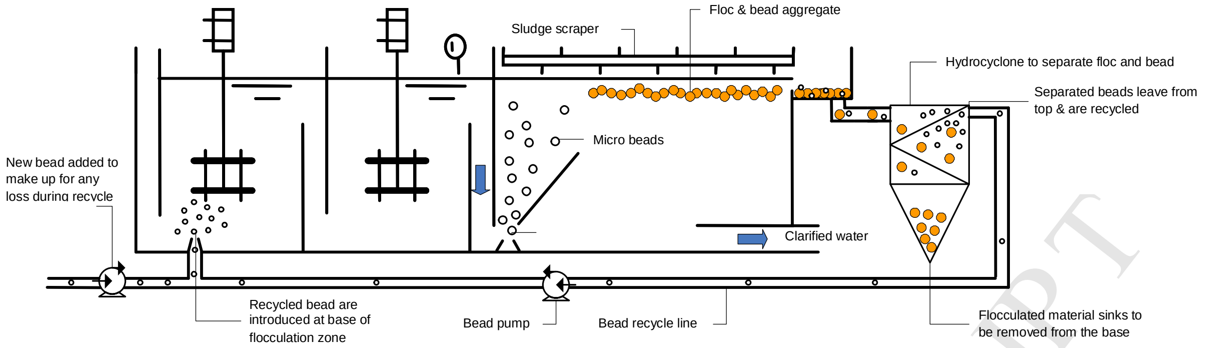

Microcystis - with bead
Microcystis - no bead
Melosira - with bead
Melosira - no bead
Chlorella - with bead
Chlorella - no bead
Algae removal (%)
0
20
40
60
80
100
Recycle ratio (%)
0
2
6
10


No bead
With bead
Floc median size (µm)
0
100
200
300
400
500
600
0
2
4
6
8
10
12
14
16
18
Time (mins)
210 µm


SI 100
Floc - no beads added
Floc - with bead
% volume
0
2
4
6
8
10
12
14
16
10
100
1000
10000
Bead Size (µm)


Number of beads in floc
Floc settling/rise rate (m.h-1)
Sedimen.
Flotation
1
0
-1
-2
-3
-4
-5
-6
-7
0
10
20
30
1010 kg.m-3
1020 kg.m-3
1030 kg.m-3
1040 kg.m-3
1050 kg.m-3
1060 kg.m-3


Number of beads in floc
Floc settling/rise rate (m.h-1)
Sedimen.
Flotation
10
0
-10
-20
-30
-40
-50
-60
0
100
200
300
400
500
100 um floc
200 um floc
300 um floc
400 um floc
500 um floc
750 um floc
1000 um floc


Floc & bead aggregate
Sludge scraper
Hydrocyclone to separate floc and bead
Separated beads leave from top & are recycled
Micro beads
New bead added to make up for any loss during recycle
Clarified water
Recycled bead are introduced at base of flocculation zone
Bead pump
Bead recycle line
Flocculated material sinks to be removed from the base