Effect of container geometry on colloids removal from water in oscillation-based flocculation

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ABSTRACT

Colloid removal in water treatment plants is commonly done by a sequence of processes that includes coagulation, flocculation, sedimentation, and filtration. The current study presents an innovative technique, termed grouping, for the removal of these suspended particles based on physical flow manipulation, which causes the particles to aggregate. Previous results showed that gentle oscillation in a cylindrical container facilitates simultaneous flocculation and sedimentation in the same reactor over shorter periods of time than are possible using the conventional treatment approach. This finding may confer marked improvements on the processes used today by enabling the use of both smaller reactors and less energy. Based on the findings with the cylindrical vessel, here the grouping technique is further examined in a rectangular container and over a range of different initial turbidities. The results indicate that the removal efficiency is higher in the rectangular container under the different initial turbidities tested. In addition, the removal efficiency was shown to remain robust with the decreases in initial turbidity and alum concentrations that occur during treatment. The positive results of our previous study taken together with this finding hint at the strong potential of the grouping technique to improve common flocculation processes.

Key words | coagulation, colloids, flocculation, oscillation, turbidity, water treatment

INTRODUCTION

Inorganic particulates, including clay, silt and mineral oxides, exist in natural surface water. Because they can adsorb toxic compounds (e.g. heavy metals), provide a sheltered environment for viruses, bacteria and protozoa, and cause turbidity in and impart color to the water, these substances should be separated from water as an essential part of its treatment for human use (Sartor et al. 1974; Montgomery 1985; Vega et al. 1998). Common particle removal processes comprise sedimentation, filtration and coagulation/flocculation (termed herein flocculation) (US EPA 2002). The flocculation process, which increases the tendency of small particles to clump into larger aggregates (Letterman 1999), entails the use of chemical additives (usually a trivalent metal ion). Addition of chemical additives destabilizes the treated solution and enables the formation of micro-flocs (coupling of chemicals and particles) that subsequently become settleable aggregates or that can be removed by filtration (Visser 1995; Hendricks 2010).

In this study, we further analyze an innovative technique, termed grouping, for the removal of mineral colloids from water. The phenomenon of grouping describes the tendency of particles and droplets in an oscillating flow to gather into groups, the essence of which depends on flow and particle characteristics. Insofar as grouping is governed mainly by parameters such as the frequency and amplitude of the velocity oscillations and particle size (Katoshevski et al. 2005; Katoshevski 2006; Katoshevski & Chkhartishvili 2018; Gupta et al. 2019), particles in the tested solutions were shown to accommodate to the oscillating flow by forming separate clusters travelling at a constant velocity equal to the phase velocity. Moreover, smaller particles were
observed to have a greater tendency to form more stable groupings. The published mathematical analyses upon which grouping is based (Katoshevski et al. 2005; Katoshevski 2006; Winter et al. 2007; Katoshevski et al. 2008; Dagan et al. 2017; Roth et al. 2017) were the motivation for our previous study in which the grouping technique was exploited to separate mineral colloids from water. In that study, we have shown that the use of oscillation-enhanced grouping under gentle conditions promote simultaneous aggregation and sedimentation. The co-occurrence of these two processes, in turn, can facilitate significant reductions in the reactor sizes and process times commonly used for flocculation and sedimentation processes (Halfi et al. 2018).

The goal of the current study was to explore the grouping technique over a wide range of initial turbidities while testing the effect of conducting the experiment in a rectangular container rather than the cylindrical container used in our previous study (Halfi et al. 2018).

MATERIALS AND METHODS

The innovative grouping technique for the separation of colloidal minerals was tested under various initial turbidities and with two different container geometries, cylindrical measuring 18 cm (height)*14 cm (diameter) and rectangular with dimensions of 11 cm*11 cm*19 cm.

Experiment solution

Experimental suspensions were prepared by using a synthetic solution that simulated a typical surface water composition containing the following ion concentrations: 100 mg L⁻¹ of NaCl, 50 mg L⁻¹ of NaHCO₃ and 30 mg L⁻¹ of CaCl₂ in 1.5 L of distilled water with DDW standard. pH was set at 7.2 ± 0.2, water temperature at 23 ± 2 °C, and conductivity <0.5 ± 0.2 μs/m. Initial turbidity was set to 50 NTU, or equivalent to a suspended solid concentration of 170 mg/L, by adding Kaolin clay from a stock solution at a concentration of 10 g/L that was stirred for at least 12 h before the experiment. Experiments were carried out using a hydrophobic colloidal form of Kaolin clay with a nanotube shape whose linear formula was Al₂Si₂O₅(OH)₄·2H₂O.

Oscillation test

The oscillator was designed to generate an oscillating flow by using an accurate sinus wave with a wide range of frequencies and amplitudes [for a detailed description, see Halfi et al. 2018]. This assembly provided the essential controlled and accurate oscillating motion, which can be optimized and compared with mathematical models and numerical simulations.

Experimental plan

The experiment was divided into two parts. In part A, solutions with different initial turbidities were treated by oscillating flow in a cylindrical container. The operational parameter for this part followed the work of Halfi et al. (2018). In part B, the optimal oscillation amplitude for a rectangular container was determined and then utilized to separate mineral colloids from solutions with different initial turbidities. Finally, a comparison between the different geometries is reported. Performances in all stages were determined by calculating removal percentage, R (%), by using Equation (1) at three time points: after 15 min of flocculation, at the end of flocculation (30 min), and at the end of the settling phase (60 min).

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R(\%) = \frac{NTU_o - NTU}{NTU_o} \times 100
\]

where \(NTU_o\) is the initial turbidity of the suspension just before coagulation and \(NTU\) is the turbidity at the sample time point.

All experiments were repeated at least three times for statistical validation. In part A, four different initial NTU values (5, 10, 20 and 50 NTU) were compared under an oscillation frequency and amplitude of 0.5 Hz and 20 mm, respectively. The experimental procedure for part A was as follows: 1.5 L of the experiment solution was added to four different beakers. Alum solutions (Al₂(SO₄)₃·16H₂O) were then added to the beakers as a coagulant at the following concentrations: beaker 1 (control) contained 0 mg/L and beakers 2, 3, and 4 contained 5, 10, and 20 mg/L alum, respectively. This was followed by 1 min of rapid mixing (100 RPM) in the jar test (coagulation phase),
29 min of oscillation in the oscillator (flocculation phase), and 30 min of settling with no motion of the paddles (settling phase).

In part B, three different amplitudes (20, 40 and 60 mm) were compared. For all amplitudes, a constant paddle velocity was maintained by adjusting the frequency. The goal of the comparison was to determine the optimal amplitude for operation of the rectangular oscillation tank. The experimental procedure for part B was identical to that of part A with the exception of the initial turbidity, which was set at 50 NTU for all tests in part B. The amplitude identified as optimal was then used to examine the treatment of solutions with different initial turbidities (5, 20 and 50 NTU). Finally, the performances of grouping in the different geometrical containers was compared. The sampling procedure used for parts A and B of the study is detailed in Table 1.

**RESULTS AND DISCUSSION**

Separation of mineral colloids in solutions with different initial NTU values in a cylindrical tank

In Halfi *et al.* (2018), the optimal oscillation frequency and amplitude for the 2 L cylindrical beaker were determined to be 0.5 Hz and 20 mm, respectively, which yielded high removal efficiency for solutions with an initial turbidity of 50 NTU when using an alum concentration of 10 or 20 mg/L. The current study examined the removal efficiency for a range of initial turbidities under the same operational parameters. The main findings are summarized in Figure 1.

When no coagulant was added, a general trend of decreasing removal efficiency was observed the lower the initial turbidity and alum concentration. This finding was expected since the grouping technology is characterized as a physical rather than a chemical process. Therefore, it leads to the formation of separate groups, but in the absence of the chemical additive, the particles will repel each other due to electrostatic forces. In this regard, increasing doses of coagulant usually improve the process until a certain dose which causes an opposite effect. This is part of process optimization, to select the right concentration and operation conditions. With the addition of coagulants, turbidity was reduced considerably for all alum concentrations and all initial NTU values already after 15 min of oscillation (Figure 1(a)). After 30 min of oscillation, the turbidity measurements for all initial NTU levels when using 10 and 20 mg/L alum (Figure 1(b)) exhibit NTU values of approximately 3. After the settling stage, NTU values of 0.5 to 1.3 were obtained when using alum concentrations of 10 and 20 mg/L for all the initial NTU values. An analysis of variance (ANOVA) test was conducted, with a confidence interval of 0.05, to test the removal efficiency of the different initial NTU values. At this confidence level, no significant statistical differences were found, indicating that a reduction in the initial turbidity by an order of magnitude is feasible.

**Rectangular tank**

Since different water container geometries may have an effect in some operational systems, the authors investigated the feasibility of using a rectangular rather than a circular solution container. Insofar as flocs sediment in the cylindrical container in distinguished settling zones formed by the periodic vortexes generated by the oscillation motion (Figure 2(a)), the rectangular container geometry was also tested for its potential to improve removal efficiencies by increasing the size and incidence of the turbulent regions.

**Optimization of the oscillation parameters in the rectangular tank**

In preliminary tests, three different amplitudes were examined to determine the optimal operational parameters for
the oscillation motion in a rectangular tank. Paddle velocity was set at a constant speed that was similar to the optimal velocity obtained in the previous study in the cylindrical container (Halfi et al. 2014), and the oscillation frequency was adjusted accordingly (Table 2).

At a significance level of 0.1, the average removal after 15 min of oscillating motion differs between the cylindrical and rectangular tanks with the 40 mm oscillation amplitude. Examination of the two other sampling times at the same confidence level, however, showed no significant difference.
A similar lack of significant difference (with confidence level of 0.1) was also observed for the different amplitudes at the tested sampling times, a finding that is possibly indicative of a main effect of paddle velocity, which was kept constant. However, a slightly higher removal efficiency was observed when using the 40 mm amplitude paddle. Indeed, the flocs generated by the 20 mm amplitude paddle were smaller (Figure 2(b)). Furthermore, the settling zone was not symmetrical and smaller, limited to the area close to the container’s perimeter, when using an amplitude of 60 mm (Figure 2(d)). It seems that for these dimensions of the rectangular container an amplitude of 40 mm is optimal both for generating the largest flocs and a symmetrical flow field, which results in organized and large settling zones (Figure 2(c)).

In conclusion, the sedimentation patterns indicate similar flow configurations for the different geometric containers and optimal parameters for promoting floc formation and sedimentation. The optimal oscillation frequency and amplitude for the rectangular container were thus set to 0.25 Hz and 40 mm respectively.

**Separation of mineral colloids in solutions with different initial NTU values in a rectangular tank**

Using the optimal oscillation parameters determined in the preliminary tests, three different initial NTU values were examined in the rectangular tank. The main findings are summarized in Figure 3.

Similar to our observations of colloid separation in the cylindrical tank, here, too, we found that the turbidity was significantly reduced for all alum concentrations and all initial NTU values. Furthermore, any differences observed in turbidity reduction for the different initial NTU values were not statistically significant. The results also indicate that the average removal percentages attained with the rectangular tank were higher than those achieved with the cylindrical tank (Figure 4).

The tendency toward better colloid removal efficiencies in the rectangular container may be due to its larger turbulence areas, a direct result of the higher amplitude applied, which was twice as strong as in the cylindrical tank.
In addition, it may also be the result of the different behaviors of the particles in the two tank geometries: the rectangular tank’s shape deflects them back into the turbulent zone, where they are captured, whereas in the cylindrical tank, only after they are transported along the perimeter of the tank do they enter the turbulent zone.

As shown in Figure 5, two vortexes are generated, one clockwise and the other counterclockwise, immediately after the change in paddle direction. The upper turbulence continues to propagate toward the upper left corner while the lower turbulence follows behind the paddle. Paddle motion in the other direction (left to right) generates similar vortexes (but opposite in direction) behind the paddle.

**SUMMARY AND CONCLUSIONS**

The separation of mineral colloids from water by using an oscillating flow was examined under different initial turbidities in a rectangular tank and compared to the results obtained in a cylindrical tank. We found that the removal efficiency of the grouping technique remained robust as the initial turbidity declined. The optimal oscillation frequency and amplitude for a rectangular tank measuring $10 \times 10 \times 19$ cm were 0.25 Hz and 4 cm, respectively. Lastly, the functionality of the rectangular container was better than that of the cylindrical tank under the operational parameters and water turbidities tested. These findings show the strong potential of the grouping technique to improve common flocculation processes, particularly when using a rectangular container.

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