High G Flocculation

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Abstract

The High G Flocculation team this semester designed an experimental set-up to test the effects of velocity gradient (G) in a flocculator and to determine the optimal G value based on flocculator performance in terms of effluent turbidity. The G value was varied in different trials by varying flocculator flow rate while controlling for coagulant dosage, influent turbidity, flocculation tube length, and upflow velocity through the sedimentation tank. $G\theta$ was kept constant at around 20000. The constant sedimentation tank upflow velocity was achieved using a waste stream between the flocculator outlet and sedimentation tank. It was found that for a standard coagulant dose, lower G values were associated with lower effluent turbidity, with 100 Hz being the lowest value tested. The same general relationship was observed for a higher coagulant dose, except that the lowest G value resulted in higher effluent turbidity due to floc blanket collapse. Data from this study will be used in the future to inform the geometry of the flocculator, i.e. the optimal distances between baffles, in a full-scale water treatment plant.

Introduction

The particle shear in a flocculator, controlled by the velocity gradient (G), is a key factor in the formation of flocs from clay particles and coagulant. Flocs are clusters of clay particles, also called platelets, held together by coagulant. When the outer surfaces of clay particles have some percentage covered in coagulant, and the particles are subject to collisions, there is a chance that there will be small coagulant particles in between the colliding clay platelets. Such a situation allows positively charged coagulant particles to neutralize the negatively charged clay platelets, resulting in a successful collision in which a floc forms due to electrostatic attraction. For these collisions to occur in the first place, a flocculator subjects the flow to a specified velocity gradient. The clay particles scattered through the flow thus move at different velocities and are more likely to collide with each other.

Due to the velocity gradient produced, fluid flowing through a flocculator at a given point and time moves in layers of slightly varying velocities. This produces a shear stress between the fluid layers. The degree to which the fluid is resistant to deformation under this stress is expressed as viscous shear. This is of interest to AguaClara because past research has revealed that viscous shear contributes substantially to the rate of floc formation. To a certain extent, greater velocity and viscous shear increase the velocity gradient, consequently decreasing the time between collisions and increasing the rate of floc formation. However increasing the velocity gradient to a very high value, results in large flocs with very high rotational velocity. Its is hypothesized that these large, fast-spinning flocs cannot combine with smaller flocs since their rotational velocity makes them throw off smaller particles in what would otherwise be a successful collision. Moreover, a very high velocity gradient will subject large flocs to a high shear force and might cause them to break apart. Since large flocs cannot combine with small flocs, there is added complexity in the problem and some amount of floc breakage may be desirable. Therefore, there must be an optimal G value in between these two extremes that produces the highest possible collision rate while preventing flocs from becoming unable to combine with smaller flocs or liable to breakage.

The breakage of flocs is theoretically problematic because smaller particles travel at higher velocities within a tube settler with some vertical component, and consequently flow out the top of the settler with the effluent. Specifically, "capture velocity" is the highest velocity that a floc particle can attain in a tube settler and still settle. This is also the speed at which a particle travels from the top to the bottom of the sedimentation plate along the entire length of the plate. Capture velocity is determined by the geometry and upflow velocity of the tube settler. However, whether an individual floc particle travels at or below this capture velocity within the tube settler is dependent on the size of the floc particle. As floc size increases, drag force encountered by the particle on its way through the tube settler increases, slowing the rate at which it travels. When this drag force is sufficiently high, the particle remains suspended, particularly closer to the walls of the tube settler where upflow velocity is at a minimum. Thus in order to form a floc blanket, it is crucial that flocs attain and remain at a certain minimum size. The greater the density of the floc particle, the lower the buoyancy force that the particle encounters, and therefore density is also a factor in the rate at which particles settle. In the experiments run this semester, floc density was not varied.

In a well-designed hydraulic flocculator, where the maximum energy dissipation is less than twice the average energy dissipation rate, the effect of floc breakage is negligible. This is because the forces that could potentially tear apart the flocs are smaller in magnitude than the electrostatic forces holding the flocs together. The flocculator used by the High G Flocculation team was designed to fit this criterion, thus floc breakup was not a concern in this experiment.

High G Flocculation worked on experimentally determining the ideal G value for flocculator performance by varying the G and θ (residence time) values through the flocculator while keeping all other variables in the setup constant. The product of G and θ, representing total number of collisions, was kept constant at around 20,000. This was done by varying the flow rate through the flocculator while keeping the inner diameter and length of the tubing constant. An increase in flow rate thus corresponded with both an increase in G and a reduction in θ. There was a waste stream between the flocculator and the sedimentation tank to ensure that the upflow velocity through the sedimentation tank is constant while the flow rate through the flocculator is varied.

Since Gθ was kept constant, the collisions rate of particles was constant through different trials. Thus, the primary effect of increasing G was that particles collided with higher magnitude velocities, although the number of collisions is about the same through trials. A higher G value is likely to result in fewer collisions that actually result in formation of a floc, because the particles do not aggregate as easily. This leads to two possibilities with either improved or worsened overall clay removal. The first possibility is that floc size is limited, and thus flocs don't get so big that they cannot combine with smaller flocs. Thus, the number of small flocs that escape the sedimentation process is limited and effluent turbidity is low. The second possibility is that many of the flocs cannot get big enough to be captured in the sedimentation tank since aggregation is less likely. This leads to higher effluent tubidity.

Having an estimate for the optimal value of G can offer insight into the true relationship between G and particle removal efficiency. If G has a significant impact on effluent turbidity, then the flocculator baffle spacing, baffle size, and cross-sectional area can be designed to produce the ideal velocity gradient, leading to more consistent effluent turbidity results. While AguaClara plants consistently meet drinking water standards for Honduras, they do not consistently meet US EPA standards, thus improvements in plant design that produce predictable reductions in effluent turbidity will bring the team closer to fulfilling clean water needs in various countries including the US. In addition, the optimization of channel size, baffle number, and baffle size can reduce the use of unnecessary material.

Literature Review

The product of velocity gradient, G and residence time, θ, was has been used as parameter for designing flocculators for many decades. The product of these two terms, Gθ is often referred to as collision potential. Various other parameters have been shown to affect flocculation since then, including coagulant dose, volume fraction and attachment efficiency O'Melia (1972); Kawamura (1991). The High G Flocculation team attempted to isolate the velocity gradient and residence time as variables affecting flocculation while controlling for all other variables. Based on recommendations from Monroe Weber-Shirk, the product, Gθ was maintained constant at around 20000, since an increase in G corresponded with a reduction in θ.

It is unclear whether floc formation in a hydraulic flocculator is dominated by interial forces, ie. turbulence, or viscous shear (Pennock et al., 2016). The experimental setup designed by the High G Flocculation team only produces flow with Reynolds numbers (Re) less than 2000, meaning that the effect of turbulence is not observed in these experiments. The team could thus isolate the effect of G, i.e. viscous shear on the process of flocculation.

Theoretically, it is unclear how changing G might affect the performance of the flocculator in terms of effluent turbidity. It is necessary that flocs be large enough to be captured during the sedimentation process. However, there is evidence that small flocs do not combine with big flocs, although the exact mechanism for this is not clear (Swetland et al., 2014). Research has shown that to an extent, a high G value will produce flocs that are smaller and more dense (Carissimi et al., 2007), allowing them to combine more effectively with other flocs. However, Gardland et al in 2016 demonstrated that G values above a certain threshold might produce flocs that are small enough to escape during the sedimentation process, leading to higher effluent turbidity. Another factor to bear in mind is that the reduction in residence time associated with an increase in G can prevent flocs from becoming too big (Garland et al., 2017).

While studies have been conducted on the relationship between G and median floc size, there is limited literature on the relationship between G and effluent turbidity. The High G Flocculation team concluded that effluent turbidity is a better indicator of the effectiveness of flocculation than floc size distribution. Since the goal of water treatment is to obtain the cleanest effluent, the effectiveness of flocculation is best evaluated based on what proportion of flocs or clay particles manage to escape in the sedimentation process with all other parameters controlled. Effluent turbidity post-sedimentation is a good measure of the proportion of escaped flocs, with

AWWA/ASCE (2012) recommends that G values lie in the range of 20 to 75 Hz. A study conducted by Serra et al. (2008) indicates that for three different methods of mechanical flocculation, G values between 15 Hz and 30 Hz are most effective at creating the largest median floc size, normalized by initial floc size. However, Garland et al. (2017) demonstrated that increasing G from 74 to 250 Hz and reducing θ from 269 to 80 s could produce cleaner effluent, suggesting that design recommendations for G values may need to be re-evaluated. The High G Flocculation team attempted to build on these findings by exploring the effects of higher G values ranging from 100 Hz to 1000 Hz, and the corresponding reduced residence times.

The velocity gradient G in a flocculator can be expressed as a function of the energy dissipation rate and the viscosity of the water, where G is velocity gradient, ϵ is energy dissipation rate, and ν is the viscosity of water.

$$G = \frac{\sqrt[2]{\epsilon}}{\sqrt[2]{\nu}} \tag{1}$$

The energy dissipation rate is dependent on velocity through the following relationship, where V is velocity, H_e is the height of one expansion zone in a hydraulic flocculator, K_e is a coefficient based on the pipe used and flow rate:

$$\epsilon = K_e \frac{V^2}{2 * H_e} \tag{2}$$

Viscosity can only be varied with temperature, thus it is not feasible to vary this. In order to vary G at a near-constant temperature, the energy dissipation rate must be varied. The energy dissipation is a function of the velocity of the fluid. Since the High G Flocculation team used a coiled tube as a flocculator in the experimental setup, the velocity could be varied by changing tube diameter or flow rate. Since it was time and cost-efficient to use the same apparatus, i.e. not varying the tube diameter, the team decided to vary the flow rate for this purpose.

Methods

Experimental Apparatus

Each of the HRS, Fluoride, Contact Chamber, and Humic Acid subteams carried out their experiments with similar setups using flocculators and sedimentation tubes identical to those used by the High G Flocculation subteam. Influent turbidity, coagulant dosage, and residence time within the sedimentation tank were pre-established by all subteams involved, as summarized in Table 1. The sedimentation tube design was based on that of the Summer 2017 High Rate Sedimentation subteam (Galantino and Kang, 2017).

Table 1: Flocculator Parameters

Symbol	Parameter	Value
V_{sed}	Sed tank upflow velocity	2 mm/s
D_{sed}	Sed tank inner diameter	2.54 cm
$Q_{sed}, Q_{reactor}$	Flow rate (based on sed tank velocity)	1.52 mL/s
$D_{floctube}$	Floc tube inner diameter	0.43 cm
R_c	Radius of curvature of floc coils	5 cm
$G\ \theta$	Product of velocity gradient and residence time	20000
G	Velocity gradient	176 Hz
θ	Residence time	114 s
L_{floc}	Length of flocculator tubing	11.8 m
ϵ_{floc}	Energy dissipation rate	30.8 mW/kg

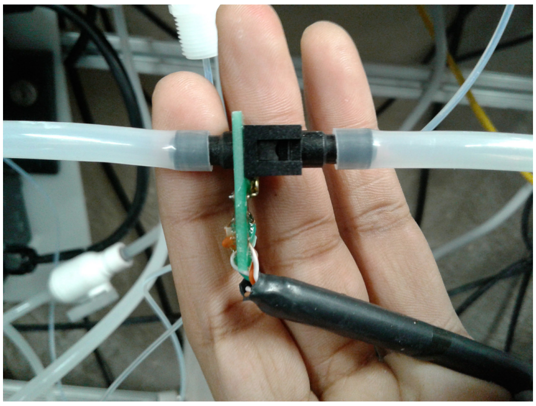
The setup consisted of five pumps, separate clay and coagulant reservoirs, a flocculator, and a tube settler, as summarized in Table2. A photograph of the setup can be found in Figure 1.

Table 2: Materials Required for Apparatus

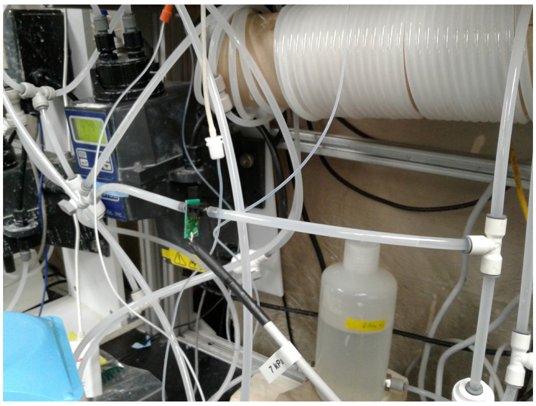
Equipment	Function
Water pump	Controls velocity of clay solution in flocculator to vary velocity gradient (G).
Clay pump	Maintains constant clay concentration with PID control.
Coagulant pump	Maintains constant coagulant concentration with constant velocity.
Effluent pump	Maintains upflow velocity within the tube settler at 2 mm/s.
Waste pump	Removes settled floc particles that have collected in weir of tube settler.
Clay reservoir	Contains well-mixed clay stock solution.
PaCl coagulant reservoir	Contains PaCl solution of 0.014g/L concentration.
Flocculator	Coiled tube in which clay particles collide to form flocs.
Tube settler	Tube recirculator in which larger and denser floc particles settle out.

Figure 1: The High G setup.

A pressure sensor was inserted at the inlet and outlet of the flocculator to determine whether the water and flocculator pumps were maintaining a constant pressure throughout each trial. It was noted by the HRS subteam that within a single peristaltic water pump rotation, immense pressure was built and released within the flocculator. As this effect was more pronounced at lower flow rates, this introduced another variable in floc formation when varying velocity gradient. To mitigate this concern, a pressure attenuator was inserted between the water pump and the influent turbidimeter.



(a) A close-up of the sensor.



(b) The sensor is placed between the two ends of the flocculator.

Figure 3: A sensor is used to regulate the pressure difference between clay solution entering and exiting the flocculator.

It is hypothesized that the rate of floc blanket climb on the sloped section of the sedimentation tube, and therefore floc blanket density at the sloped section, is different from these metrics in the vertical portion of the tube. A video recording was used to demonstrate this and the notion that after the floc blanket approaches the floc weir, the rate of floc blanket formation reaches a new steady state at which effluent turbidity is kept constant.

Figure 2: A pressure attenuator is used to even out flow rate during each rotation of the peristaltic water pump.

Note that the tube settler represents one plate of a sedimentation tank in an AguaClara plant. Additionally, although in the laboratory setting the velocity of flow through the flocculator was varied to change the value of G, data collected on the optimal G value of the flocculator will inform the geometry of the flocculator (i.e. the optimal distances between baffles) rather than flow rate in an AguaClara plant.

Procedure

The general setup for the High G Flocculation experiments was as follows:

1. The water pump (see Figure 1) was used to vary the velocity of influent through the flocculator, and therefore to vary G in a controlled manner.
2. The clay pump contaminated clean water with a well-mixed clay solution. The pump and influent turbidimeter together used PID control to maintain a constant influent turbidity of 100 NTU.
3. The coagulant pump introduced PACl coagulant to the clay-water solution, and the solution entered the flocculator, where clay particles were made to collide and form larger flocs.
4. To account for the difference in flow between the water pump and the effluent pump, a waste stream between the flocculator and sedimentation tube maintained a constant upflow velocity through the sedimentation tube. The sedimentation tube is an apparatus that mimics the function of a sedimentation tank in a full-scale treatment plant.
5. The flocs entered the bottom of the tube settler. The larger and therefore denser particles settled out, and were carried out to the waste stream.
6. The treated water passing through the tube settler then exited the top, entered the effluent turbidimeter, and was also carried out through the waste stream, as is shown in Figure 4.
7. A waste pump was used to ensure that settled floc particles in the tube settler exited the system without clogging tubes.
8. An effluent pump ensured that the upflow velocity within the tube settler was kept at 2 mm/s, as recommended by the HRS subteam.

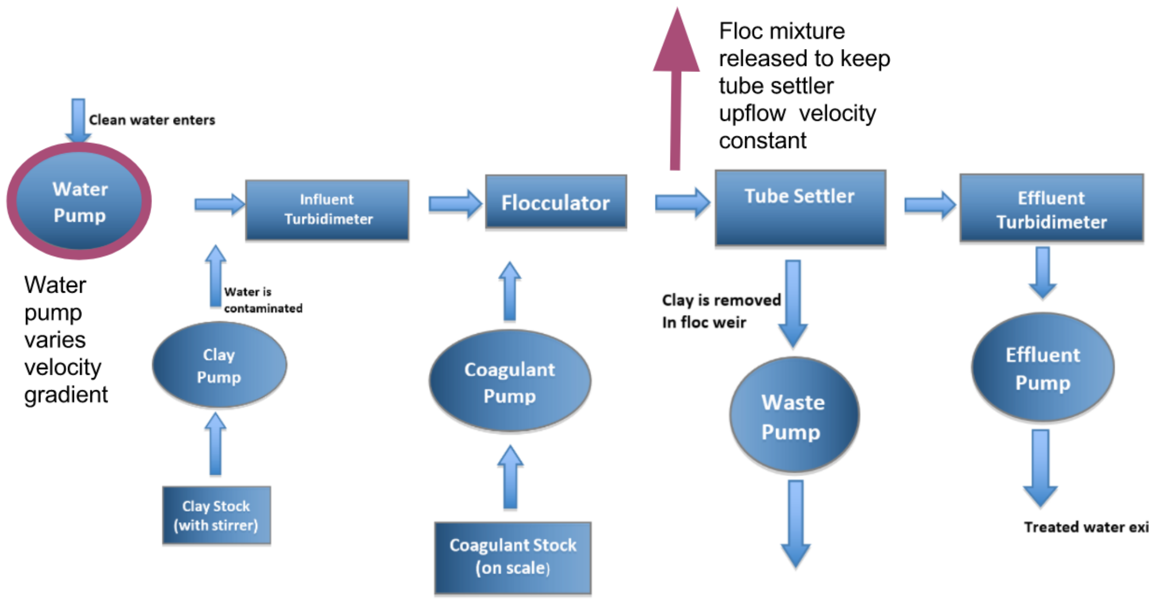


Figure 4: The waste stream between the flocculator and the sedimentation tank keeps the upflow velocity through the tube settler constant.

Results and Analysis

Trials were run at seven different G values with theta values to keep $G\theta$ constant. The results are summarized in the table below. Additional trials were run to test the 100, 200, 300 and 500 Hz G values at a higher coagulant dosage and to demonstrate that the relationship between G and effluent turbidity holds at different PACl dosages.

Table 3: Minimum and Steady-State NTU Varying Velocity Gradient G at 1.4 mg/L PACl Concentration

G (Hz)	Min. Turbidity (NTU)	Steady State Turbidity (NTU)
100	1.13	1.8 - 2.5
200	1.72	2.2 - 3.0
300	2.01	2.5 - 3.1
400	4.74	5.5- 6.7
500	5.59	6.2- 7.0
750	16.97	17 - 17.5
1000	80.00	80 - 95

Table 4: Min and Steady-State NTU Varying Velocity Gradient G at 7.0 mg/L PACl Concentration

G (Hz)	Minimum Turbidity (NTU)	Steady State Turbidy (NTU)
100	2.69	3.0 - 5.0
200	0.21	0.4 - 0.5
300	0.71	1.5 - 2.0
500	TBD	TBD

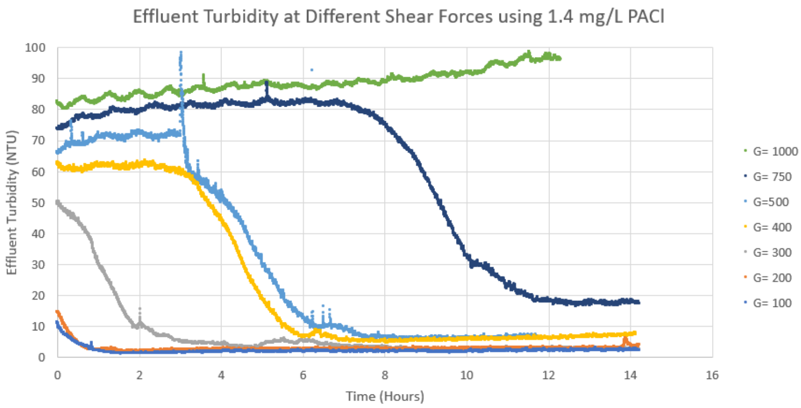


Figure 5: Effluent turbidity at values of velocity gradient (G) between 100 and 1000 Hz. Gθ is 20,000 Hz and coagulant dosage is 1.4 mg/L for all trials.

Figure 5 depicts effluent turbidity at six different values of shear velocity (G) between 100 and 1000 Hz. Within this range, it was determined that a lower G value yields better clay removal and lower effluent turbidity over the course of twelve hours. When G holds a value of 1000 Hz, no floc blanket was able to form and clay removal worsened throughout the experiment as indicated by the increasing effluent turbidity.

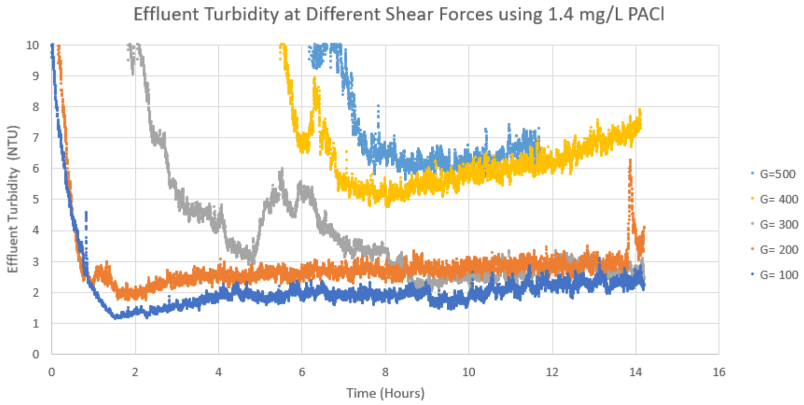


Figure 6: A close-up of Figure 5. The system at lower G values within the range of 100 and 1000 Hz produced lower steady-state effluent turbidity, and reached this steady state in less time. Gθ is 20,000 Hz and coagulant dosage is 1.4 mg/L for all trials.

As depicted in Figure 6, the experimental results show that for lower G values, lower steady-state effluent turbidities were reached.

For the standard coagulant dose of 1.4 mg/L, a G value of 100 Hz provided the best removal. Removal of clay was slightly worse when increasing G from 100 Hz up to 300 Hz, and significantly worse above 400 Hz. The most likely explanations for this result, as is corroborated by previous research, is that the higher G values result in limitation of floc size. When subjected to a high velocity gradient, floc collisions may not result in sufficient floc aggregation, resulting in floc sizes small enough that they can escape the sedimentation process. This results in higher effluent turbidity.

This physical explanation is supported by qualitative visual observations. The floc coming out of the flocculator and entering the tube settler were observed to be smaller for higher G values. These qualitative observations can be confirmed through more rigorous measurement of floc size using the Floc Size and Count App produced by AguaClara students.

It is also observed in Figure 5 that different G values display similar slopes in effluent turbidity before achieving steady state. However, the time taken to reach steady state and the turbidity associated with each steady state differs for the various G values. Based on timed video footage, the sloped regions in the graphs represent the formation of floc blankets, while the steady state is achieved once the floc blanket is fully formed. This suggests that different G values are associated with different times until floc blanket formation, and that the floc blanket does the bulk of the removal of clay. The differences in steady-state effluent turbidity are due to both differences in the size of flocs moving through the floc blanket, and the density of the floc blanket itself.

At a G value of 1000 Hz, velocity gradient between fluid layers in the flocculator was so high that the force of attraction between clay and coagulant particles was unable to overcome the separating shear force, and few flocs were formed. Consequently, no floc blanket formed in the sedimentation tank and further floc formation and clay removal remained low.

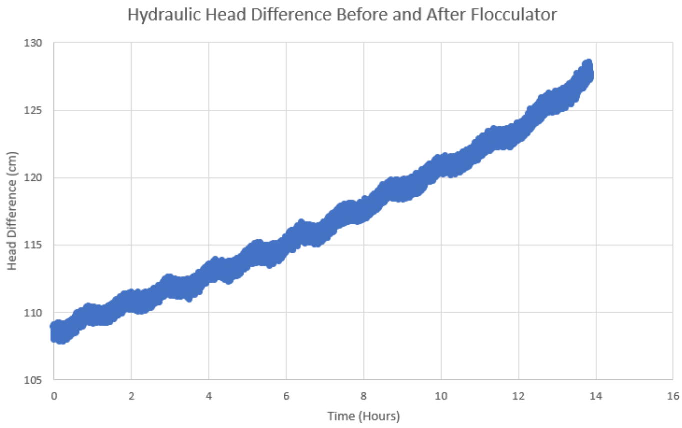


Figure 7: Hydraulic head difference between the influent and effluent through the flocculator.

A pressure sensor was used to demonstrate that hydraulic head between the influent and effluent through the flocculator increased over the course of each trial. Figure 7, for the trial in which theoretical velocity gradient is kept at 300 Hz, is used as a sample to show this increase in pressure difference with respect to time. It is hypothesized that this pressure difference was due to a buildup of coagulant or clay on the inside walls of the flocculator tubing. This reduces the inner diameter of the tubing, resulting in higher velocity for the same flow rate. This would imply that the longer a trial was run, the greater the shear force and velocity gradient (G) was within the flocculator, allowing the experimental value of G to exceed the theoretical G value.

$$h_{Linitial} = 108cm$$
$$h_{Lfinal} = 128cm$$
$$G_{initial} = \sqrt{\frac{gh_{Linitial}}{\nu\theta}} = 300Hz$$
$$G_{final} = \sqrt{\frac{gh_{Lfinal}}{\nu\theta}} > 326.4Hz$$

From the head difference graph, hydraulic head increases from 108 cm to 128 cm from the beginning to the end of the G = 300 Hz trial. With a higher velocity, theta through the flocculator will decrease as well, further increasing G. This new G value was not directly measured in the experiment. However, knowing theta decreases, it can be said that from the start of the trial, G increases by at least 26.4 Hz or by at least 8.8 %. For all the trials, hydraulic head increases throughout, raising G, and likely contributing to the slight gradual increase in steady state effluent turbidity as each trial progresses.

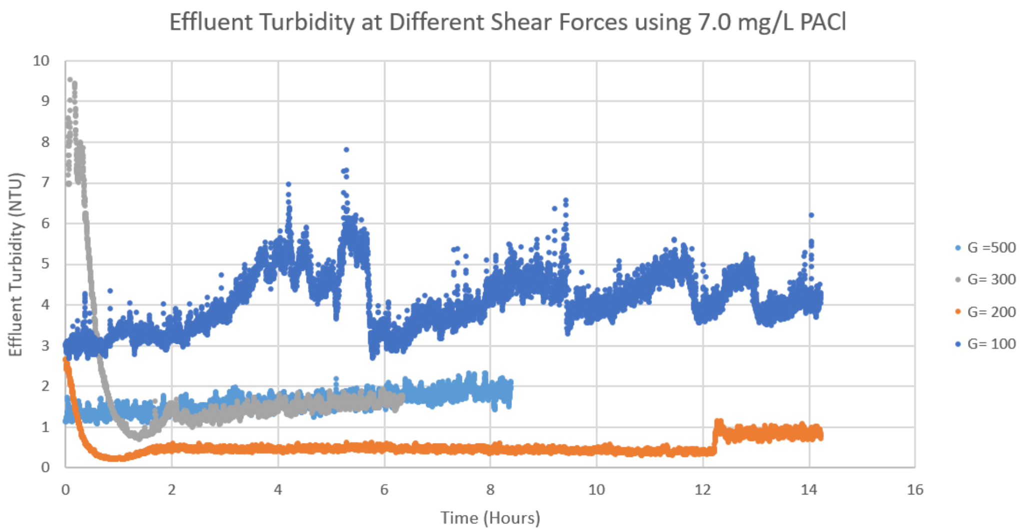


Figure 8: Effluent turbidity at six different values of shear velocity (G) between 100 and 1000 Hz. $G\theta$ is 20,000 Hz and coagulant dosage is 7.0 mg/L for all trials.

When conducting trials at the higher coagulant dose of 7 mg/L, it was found that the general relationship between velocity gradient and effluent turbidity found in the 1.4 mg/L dose trials still held, with lower G values resulting in lower effluent turbidity. However, a higher removal was achieved at the trial for which G value was 200 Hz than for the trial at which G was 100 Hz.

At a G value of 100 Hz, individual floc particles became large and sticky enough that they could not be resuspended in the jet entering the tube settler. Instead of traveling upward to contribute to floc blanket formation, the larger, coagulant-coated flocs ended up sticking to the sloped bottom walls of the tube settler. Thus, instead of forming a suspended floc blanket, the flocs piled up near the bottom of the tube settler to form a 'collapsed floc blanket'. There is videographic evidence of this mechanism from research conducted by Garland et. al. 2017 (Garland et al., 2017)

Without being fluidized, most sections of this collapsed floc blanket remained stagnant, and thus did not aid in floc aggregation as an intact floc blanket would. While the pumps on either end of the sedimentation tube kept upflow at a constant 2 mm/s, it is hypothesized that most of this flow was concentrated through a small aperture in the collapsed floc blanket, and the smaller flocs remaining exited the tube as effluent. At G values of 200 Hz and above, it is likely that the higher shear limited floc size to some extent, thus limiting the build-up of flocs on the bottom walls and preventing floc blanket collapse.

At even higher coagulant doses, there is so much positive charge coating the clay particles that they cannot stick together. This is because like charges repel each other, and when coagulant coverage of clay particles approaches 100 percent, they act as positively charged particles. Coagulant doses high enough to prevent floc formation were not tested at this time. At the 6 mg/L coagulant dose, the risk of floc blanket collapse is a restricting factor. Between the tested range of G values from 100 to 500 Hz, removal was better at 200 Hz than both 100 and 300 Hz. It could be observed in the 300 Hz trial that at a high coagulant dose and high velocity gradient, flocs get large enough to collapse the floc blanket. It is hypothesized that removal was better at 200 Hz than at 100 Hz because the former limited floc size without leading to floc blanket collapse.

In both cases, some amount of aggregation in the flocculator is required to get the floc blanket formed in the sedimentation tube. The floc blanket then facilitates further collisions and promotes further removal. Among the trials conducted for the standard dosage of 1.4 mg/L, removal is best at 100G and worsens with increasing G values. As coagulant dose increases, lower G values are more likely to lead to floc blanket collapse. Thus, the optimal G value in such cases is predicted to be higher than for lower coagulant doses.

It is worth noting that the location of the floc blanket in this experimental setup was not an ideal representation of the floc blanket that is observed in the full scale sedimentation tank. The sloped part of the tube settler is used to recreate the effect of a single slanted settling plate. In the tube settler used by the High G Flocculation team, the floc weir was represented by an outlet made of rigid tubing coming out of the sloped section of the main tube. In reality, the floc blanket forms below the slanted plates, meaning that this outlet weir should be located below the sloped part of the tube settler to truly mimic the effect of a slice of the sedimentation tank.

Conclusions

The fact that floc size does not necessarily correlate with increased removal shows that efficiency in flocculation depends not only on the flocculator's ability to aggregate particles into large flocs, but also on maximizing the ratio of clay particles that aggregate to form flocs close to a minimum floc size for capture in the sedimentation tank. For best removal, shear rates must be high enough to maintain high collision rates but low enough to allow aggregation to occur, so both velocity gradient and coagulant dosage factor into efficiency.

Although most other studies make no mention of this, it is key to note that flocculator performance must be assessed in conjunction with assessment of sedimentation tank performance. The High G subteam found that optimal G value is affected by coagulant dose. The time required for floc blanket formation was an indicator of how much the flocculator contributed to floc aggregation relative to the sedimentation tank. At low coagulant dose (ie the ability of clay particles with minimal PACl coating to aggregate is a limiting factor of removal), removal is best at 100 Hz within a G-value range of 100 and 1000 Hz. At low coagulant dose and high G, shear is too great and flocs are unable to form.

Velocity gradient is important to consider when designing flocculators in AguaClara plants. In a treatment plant, the optimal G value can be achieved given a relatively constant coagulant dosage and flow rate by adjusting the baffles accordingly: shorter, more spaced out baffles reduce G value and longer, closer baffles potentially with additional obstacles increase velocity gradient by introducing sharper turns in the path of flow. Since the best removal for standard coagulant dose was observed at a G value of 100 Hz, it would be beneficial to focus on slightly lower G values while re-evaluating AWWA/ASCE guidelines.

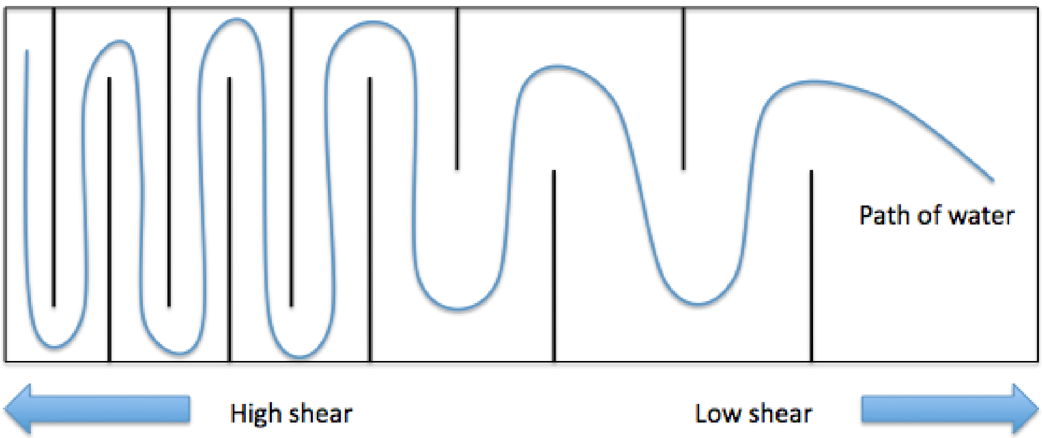


Figure 9: The flocculator of a treatment plant can be designed to maintain an optimal G value by adjusting the length of and spacing between the baffles. Increasing baffle length and decreasing distance between baffles increases the velocity gradient.

Future Work

Based on the result that among all values tested, a velocity gradient of 100 Hz produces the best clay removal efficiency for a coagulant dose of 1.4 mg/L, the next step is to conduct further tests at even lower G values, with lower increments of velocity between trials to determine an optimal G value. This value for the current set-up is likely to be higher than that recommended by current engineering guidelines, but is possibly lower than 100 Hz, the lowest tested velocity gradient. It is important to note that doing this with would require flocculator tubing with a larger diameter, and consequently decrease the amount of coagulant lost to the walls of the tube. This will need to be factored in comparisons of future results with those of the Fall 2017 experiments.

$G\theta$ was kept constant while varying G in the Fall 2017 experiments to keep constant the rate of particle collision in the flocculator while varying the energy associated with those collisions. Therefore at this time there is no perceived need to hold residence time, θ, constant to study the effect of G in isolation.

Additional research with smaller increments of G between high-coagulant trials could provide greater insight on this topic. It was shown this semester that at a coagulant concentration of 7mg/L, the floc blanket collapsed for a G value of 100 Hz but not for a G value of 200 Hz. Based on the results of this semester's work it is expected that for higher coagulant doses, low G values will result in floc blanket collapse due to higher density than desired. Thus, the optimal G for a given coagulant dose might be the smallest value for which the floc blanket does not collapse. Another approach in confirming that the relationship between shear gradient and clay removal efficiency established in the trials completed thus far is independent of coagulant dosage within an appropriate range is to maintain a constant G value while varying coagulant dosage. The end product of this experiment would be a model describing the relationship between PACl dosage and optimal G.

There may also be merit in running a setup with two consecutive flocculators with different G values. The first one would be attached at the present location of the flocculator, and the second would likely be located after the waste stream to have a lower flow rate that he first one. The difference in flow rates would allow the two flocculators to have different G values. This setup will allow teams to explore the potential for varying baffle spacing through a single flocculator in full-scale AguaClara plants.

The ideal AguaClara plant would minimize its use of coagulant due to costs, the desire to reduce environmental waste, and issues related to maintenance, as coagulant is at least as likely to stick to walls as it is to stick to free-floating particles. Thus it is beneficial to focus on the trials in which coagulant dosage in low.

Lastly, the floc weir was located at the sloped section of the tube settler, and can be repositioned to the vertical section of the tube to more accurately reflect the position of the floc weir in relation to a sedimentation plate in an AguaClara plant. This correct location could improve confidence in the results of future tests.

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Semester Schedule

Task Map

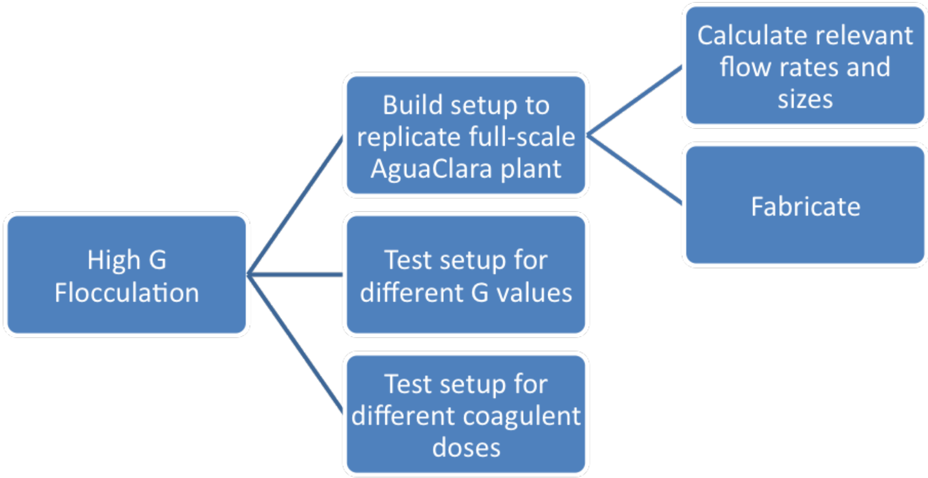

Figure 10: Above is the High G Flocculation Task Map for the Fall 2017 semester.

Task List

1. ✓Review literature (September 14) - Roswell. Go over past MathCad files from HRS team, study relevant 4540 slides on flocculation, read HRS past papers.

2. ✓Calculate relevant parameters (September 14) - Tanvi. Identify constraints from various teams, calculate tubing size and length as well as G and theta. Formulate general flocculator design for all particle removal teams.

3. ✓Fabricate apparatus (September 28) - All. Obtain 0.17 in ID tubing for flocculator, coil around cardboard tube of required radius to create flocculators for all subteams in need of one, obtain setup design and 1 in OD recirculator from HRS team, connect tubes to pumps and sed tank.

4. ✓Confirm that HRS, Fluoride, Contact Chamber, and Humic Acid subteams are using same apparatus (September 28) - Luna. Send emails and/or schedule meetings with subteams.

5. ✓Pump calibration: convert flow rate to RPM (October 12) - Tanvi. Find exact relationship between RPM and flow rate, verify that flow rate is correct repeatedly within the High G setup.

6. ✓Symposium (October 16) - Roswell. Create slideshow, rehearse presentation.

7. ✓Vary G and collect turbidity data to find optimal velocity gradient in the range of 100 to 1000 Hz (November 16) - Tanvi.

8. ✓Vary coagulant dosage at optimal velocity gradient and collect turbidity data (December 1) - Luna.

Report Proofreader: Luna Oiwa

Manual

Experimental Setup

The salient feature of the High G Flocculation setup is the waste stream between the flocculator and the tube settler. In Fall 2017, this feature was not present in any of the other particle removal teams' experimental setups. The purpose for this waste stream is to vary flow rate between the flocculator and the sedimentation tank, allowing for different G values within the flocculator while maintaining a constant upflow velocity in the sedimentation tank. The feature can be used in the future to vary G between two consecutive flocculators.

Experimental Checklist (Including Pre-experiment Cleaning)

1. Drain the sed tank after the previous trial and the flocculator if necessary.
2. Refill clay and coagulant stocks.
3. Run tap water through the system to rinse the flocculator, sed tank, and connecting tubing.
4. Rinse and refill turbidimeters.
5. Use the MathCad (or Python) coagulant dosing file to determine coagulant pump flow rate for your desired dosage.
6. Check all valves to make sure desired pathways are clear and undesired pathways are blocked.
7. Verify all influent, effluent and coagulant pumps are set to the desired flow rates for that trial.
8. Turn on influent pump to fill the sed tank will clean tap water
9. Plug in clay stock stirrer if not already plugged in.
10. Turn on influent, effluent and coagulant pumps.
11. Set state to PID control in ProCoda (this will turn on clay pump and also turn on data collection).

ProCoDA Method File

States

- <u>OFF</u> - Resting state of ProCoDA. All sensors, relays, and pumps are turned off.
- <u>PID</u>- Data collection state of ProCoDa, with Clay Pump flow rate controlled by PID to account for fluctuations in clay stock concentration