Laminar Tube Flocculation

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Abstract

Over the summer of 2014, the laminar tube flocculation team has worked to test AguaClara's new residual turbidity monitoring system, SWaT, as compwered with prior teams that used FReTA. The group has also implemented PID control for the laminar tube flocculator to regulate the amount of clay added to the system. In order to achieve these goals, the laminar tubing system was simplified and reconfigured to eliminate the feedback loop with the turbidimeter. The team plans to continue optimizing the system and confirming the self regulating controls were working before starting experiments using varying dosages of coagulant.

Literature Review

In the flocculation process, colloids and flocs collide with other colloids and flocs to form larger flocs. Because these larger flocs settle out more quickly, they can more easily be removed from the water when in the settling tank. However, it has been suggested that when flocs become large enough, colloids were less likely to attach to them due to the increased surface shear. Once a floc reaches its maximum size, colloids and flocs no longer interact in the same way and the colloid/floc collisions are likely no longer effective. Therefore, it has previously been proposed that large flocs were not useful and that better performance might be accomplished by breaking large flocs apart so that additional colloids may attach to the smaller flocs[4].

In a laminar tube flocculator such as the one used in this experimental apparatus, there is a known relationship between the velocity gradient, G, energy dissipation rate, ε, and kinematic viscosity, ν, that can be viewed below.

$$G = \sqrt{\frac{\varepsilon}{\nu}} \tag{1}$$

In laminar tube flocculators, the amount of flocculation that is expected to occur can be determined from the value of $G\theta$, where $\theta$is the hydraulic residence time. Research conducted by Ian Tse indicates that flocculator performance is best when G is small and θ is large [3].

The rate of flocculation is dependent on the energy dissipation rate throughout the flocculator. A higher energy dissipation rate corresponds to a higher velocity gradient as can be seen in equation (1). This higher velocity gradient implies that there will be a greater number of collisions in the flocculator. Higher energy dissipation rates also lead to more floc break-up. This break-up has the potential to be both beneficial and detrimental to the process. On one hand, floc break-up may cause there to be fewer settleable flocs. However, as was previously stated, it appears to be difficult for colloids to attach to large flocs, and floc break-up may therefore allow for additional flocculation.

The performance of a flocculator is measured by its residual turbidity after the colloids and flocs have aggregated and settled. An equation for residual turbidity has been proposed by Swetland, et al. [2] and can be viewed below:

$$C* = e^{\frac{-3W}{2}(\frac{2}{3}\Gamma G t \phi^{\frac{2}{3}} \frac{\eta_{Coag}}{V_{Capture}})} \tag{2}$$

where $C*$ is the residual turbidity divided by the influent turbidity; W is the lambert W function ; Γ is the fractional coverage of colloids by coagulant; G is the average velocity gradient; ϕ is the floc volume ratio; $\eta_{Coag}$is the viscosity of the coagulant and $V_{Capture}$ is the capture velocity.

Most of the flocculators in AguaClara plants experience turbulent flow as opposed to laminar. Therefore, it is important to test the findings from laminar tube flocculation in turbulent conditions as well.

Previous research on the laminar tube flocculator utilized FReTA (Flocculation Residual Turbidity Analyzer) to measure residual turbidity. However, there were fluctuations in the data due to flocs being recirculated within the glass column. Therefore, a new system was constructed to measure the residual turbidity. The new system, SWaT (Settled Water Turbidity analyzer), was a tube settler that leads to a turbidimeter. The tube settler was set at an angle of approximately 60^o to prevent flocs from rolling up the tube and recirculating. The SWaT system was utilized in the experiments associated with this paper, and data collected from it was compared to previous data collected by FReTA.

Introduction

Apparatus

A schematic for the Laminar Tube Flocculator experimental set-up can be viewed below in Figure 1. As can be seen in the schematic, various points in the plant flow were labeled with letters. A detailed overview of the plant flow and important processes occurring at each of the lettered positions can be viewed below.

a) The clay stock tank had a solution of 5 g/L of clay. To ensure the mixture was homogeneous, an electric mixer continually stirred the solution.

b) The clay stock was pumped through a peristaltic pump that was controlled by PID. PID is a Process Controller program that reads the experimental turbidity from the turbidimeter at point d) and adjusts the speed of the clay pump to alter the influent turbidity towards the desired value. The P stands for proportional and represents to what degree the system should change in response to a high or low variable reading, using the discrepancy or error value to calculate the proportion. The integrative value, I, determines how the system responds to the amount of past error based on the integral of this error over a certain amount of time. The D is the derivative value and represents how much the system is affected by the rate of change of the turbidity value. Process controller utilizes these variables to adjust the clay pump speed and, therefore, the influent turbidity that is achieved [1].

c) Raw water that had been temperature controlled in the Hollwaster B60 lab entered the system and combined with the clay stock right before entering the turbidimeter. It was important to keep the water that entered the system temperature controlled so that there were no temperature gradients that might cause flocs to recirculate when in SWaT, thereby jeopardizing the integrity of the residual turbidity readings.

d) The influent turbidimeter measured the turbidity of the influent water by shining a light through a glass vial. The amount of light that reaches a sensor after passing through the vial corresponds to the measure of suspended particles in a sample in units of NTU (Nepholometric Turbidity Units). The reading that the influent turbidimeter receives helps the PID control determine how to adjust the amount of incoming clay stock. Therefore it was important that there be as little a time delay as possible between the incoming clay stock and the turbidimeter. For this reason, the tubing connecting the clay stock was snaked through the influent turbidimeter.

e) The coagulant stock was kept at a concentration of 60 $\frac{mg}{L}$. Depending on the desired dosage of coagulant, Process Controller adjusted the speed of the peristaltic pump and, therefore, the flow rate of coagulant into the system.

f) The tight coil rapid mix consisted of tubing tightly wrapped around a plastic cylinder. The rapid mix occured right after the coagulant had been injected into the system. The purpose of the rapid mix was to allow the coagulant to attach to the colloid particles so that the particles could attach together.

g) The purpose of the flow accumulator was to absorb the unevenness of the pulses generated by the peristaltic pumps and ensure a smooth flow of water into the tube flocculators.

h) When Process Controller applies a current to a solenoid valve, a magnetic field is induced and the valve is opened. When there is no current applied, the valve remains closed. One solenoid valve was placed after the flow accumulator and before the backwash line to ensure that water flows through the flocculator and not backwards through the tight coil rapid mix during the backwash state. A second solenoid valve was installed to keep water from flowing into the backwash line when the system was not in the backwash state.

i) The three tube flocculators each consist of 1/2" tubing wrapped around two parallel $11cm$ outer diameter cardboard tubes. The tubing was arranged around the cardboard tubes in a figure eight design in order to alter the orientation of the velocity gradient and prevent flocs from settling to the bottom of the flocculator. The first and third tube flocculators were 30 m long Tygon tubing. The second flocculator in series was 23 m of silicone tubing. Previous apparatus designs utilized clips attached to the tubing to constrict the flow and promote floc break-up. However, when the clips were removed the tubing remained deformed. For this reason, the silicone tubing (which was more elastic and therefore more resistant to permanent deformation) was selected to be the tubing for the center flocculator. However, the silicone tubing was much more expensive than the Tygon tubing, so the Tygon tubing was maintained for the flocculators not used to test floc break-up.

j) A 7 k Pa pressure sensor was arranged to measure the head loss across the silicone flocculator during the floc break-up experimentation. The pressure sensor measures the head loss by reading the difference in absolute pressure between the ends of the flocculator.

k) SWaT (Settled Water Turbidity Analyzer) is the current device used for measuring the residual turbidity of the effluent water leaving the flocculator. SWaT consists of a tube settler with an outlet at the top that leads to a turbidimeter. The tube settler was a 1.04 m long PVC pipe with an inner diameter of 26.65 mm that was tilted at an angle of 60^o. Setting the tube at this angle prevents floc roll-up and allows for a capture velocity (V_c) of 0.1 to 0.5 $\frac{mm}{s}$. The flow rate through the tube settler was controlled by the peristaltic pump that was attached to the outgoing side of the connected turbidimeter.

l) The turbidimeter attached to the tube settler measured the residual turbidity after the flocs had settled to the bottom of the tube settler and cleaned water was pumped up through the tube settler.

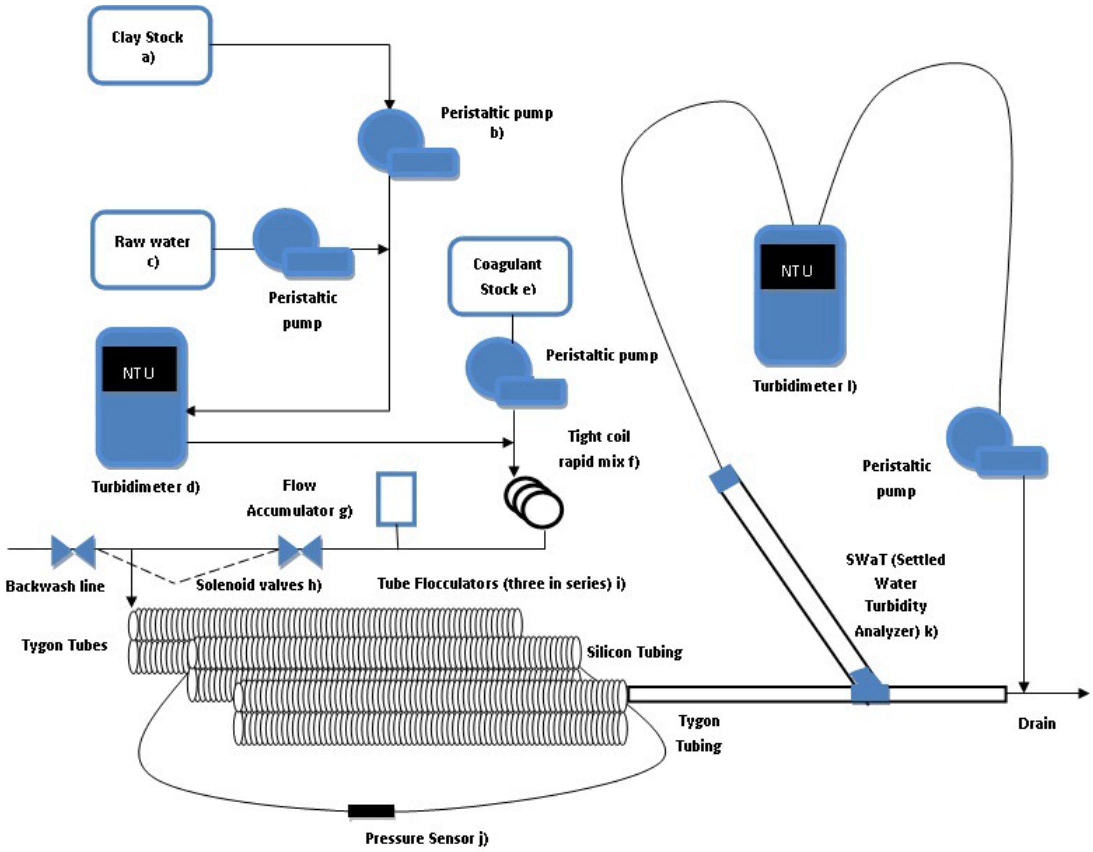

Figure 1: Laminar Tube Flocculator Schematic

Method File

Initial experiments were done with the flocculator running in an automatic cycle, which included five separate states for each PACl dosage, and which cycled through five dosages in each experiment. The five states contained in the Process Controller method file were as follows:

1) Off: In this state, all of the pumps were off and valves were closed. There was nothing flowing through the system.

2) Loading: This state was included to allow the system to achieve the appropriate level of turbidity and coagulant dosage before the actual experiment was run. In this state, tap water, clay, and coagulant all flowed through the flocculator, but not through the tube settler. The raw water solenoid valve was opened to allow the water to pass through, and the backwash water solenoid valve was closed. The tap water flowed in through a peristaltic pump at a rate of 5 mL/s. The clay was added to the system by a peristaltic pump that was

controlled by PID, in order to give the PID system time to run and establish a good baseline turbidity.

This state was also designed to account for the fact that the influent turbidity spikes dramatically every time the system begins a new cycle. this was because the PID system was initially reading a very low influent turbidity prior to the transition, which caused it to respond by adding a very large amount of clay. Because the tube settler was turned off in this state, the excess clay that was initially added should have been able to drain out from the system without interfering with effluent turbidity readings during the experiment or creating an excess buildup of flocs in the tube settler.

The coagulant was injected by a peristaltic pump whose flow rate was controlled by Process Controller based on the desired PACl dosage for the current experiment and the flow rate of the flocculator; since the system was cycling between different PACl dosages, this ensured that only the appropriate dosage was being considered during each experiment. The loading state lasted for 25-35 minutes, depending on the experiment.

3) SWaT: This was the state in which the system was run during the experiments to determine the effectiveness of settling in SWaT. The raw water solenoid valve was opened, the backwash solenoid valve was closed, and the tube settler pump was turned on to allow for settling within the SWaT system. Tap water flowed in at a rate of 5 mL/s, the clay was injected with PID control, and the PACl was dosed at a flow rate determined by the desired PACl dosage, all of which were controlled by peristaltic pumps. The influent turbidity was maintained at approximately 50 NTU. The water through the tube settler was initially pumped at a flow rate of approximately 2 mL/s, giving a capture velocity of approximately 0.17 mm/s, but this was later changed to a flow rate of 1.4 mL/s in order to achieve a capture velocity of 0.12 mm/s. The experiment was run in the SWaT state for 40 minutes.

4) Backwash with Tube: In this state, water from the backwash tube flowed forwards through the flocculator and also up through the tube settler. This clean water was used to flush out the system and then passed through the drain into the sink. In this state, the backwash water solenoid valve was open, and the raw water solenoid valve was closed in order to prevent the backwash water from moving back through the system in the wrong direction. The tap water, clay, and coagulant pumps were turned off, and only the peristaltic pump after the tube settler was turned on to facilitate the flow of water through the system. This backwash state initially lasted for ten minutes, but it was later determined that this was likely not sufficient for effective cleaning of the system.

5) Backwash without Tube: This state was designed to allow the flocs that had not escaped the tube settler to simply flow out the bottom of the tube and be drained away. In this state, the tube settler pump was turned off, and tap water was pumped forward through the system. The raw water solenoid valve was opened, and the backwash solenoid valve was closed. Tap water was pumped through the flocculator using a peristaltic pump, and the water passed out through the drain without going up the tube settler. Clay and coagulant pumps were also turned off in this state. This flushing state initially lasted for

five minutes, but again it was determined that the entire backwash system was not working sufficiently in the sequential experiments.

During experimentation, the system began in the loading state. It then cycled through the SWaT and backwash states, in the above order, before returning to the loading state and applying a new PACl dosage. Each time, the flow rate of the PACl pump was adjusted in order to achieve the appropriate coagulant dosage for that experiment, because the goal was to test the effectiveness of the flocculator across various PACl dosages. After the system had cycled through all of the necessary PACl dosages, it would turn off automatically.

Methods

Fabrication

System Modifications

Before the Laminar Tube Flocculator apparatus was ready for experimentation, some changes in the arrangement of the apparatus had to be made. First, the raw water storage tank had to be adjusted to maintain the temperature of the water in the tank at the same temperature as the room. This step was necessary to prevent temperature gradients in the water that would cause flocs to recirculate in the tube settler. The temperature control utilizes two thermistors, a pressure sensor, and software written in LabView. One thermistor was attached to the outside of the tank, exposed to the ambient temperature. The second thermistor was inserted into the side of the tank and exposed to the temperature of the water. A pressure sensor was installed at the bottom of the water tank to determine the water level of the tank and prevent the tank from overflowing. Based on the temperature readings from the two thermistors, Process Controller controls whether or not the solenoid valves were open that allowed hot and cold water to enter the tank.

Another alteration made to the apparatus was the implementation of PID control. As was mentioned before, PID was a Process Controller program that analyzes the amount of current turbidity, the rate of change in the turbidity measurement and the desired turbidity value. Depending on these values, PID alters the speed of the peristaltic pump adding clay to reach the target turbidity. The initial set-up for clay delivery was a pinch-valve system with a turbidity feedback loop. The clay stock tank had been elevated above a second tank that held the raw water. Depending on the turbidity of the influent water, the pinch valve attached to the clay stock tank would either allow clay stock to drip into the raw water tank or prevent it from flowing completely. To implement the PID system, the first task was to rearrange the tubing of the clay system. The raw water tank was removed, as was the pinch valve. Small holes had to be drilled through two 1/4" gray plugs to allow for the thin microTol tubing to go through.. These were then attached to the clay stock tank and inserted into the influent tube to allow for the injection of clay directly into the influent water, immediately before the influent turbidity reading. The thin tubing was chosen for the clay stock to minimize the amount of clay that settled to the bottom of the tubing. The first gray plug was installed in the opening of the clay stock tank and the second was installed into a T-connecter directly above the influent turbidimeter. The thin microTol tubing was threaded directly into the turbidimeter to minimize the response time of the PID system.

Experimental

Apparatus

Once the PID control was implemented, it was necessary to test the apparatus and confirm that it was performing as desired. Several runs of the flocculator and SWaT system indicated that the flocs were forming, settling out in the tube settler, sliding down and escaping through the drain tube. These experiments were run with a flow rate through the tube settler of 2 mL/s, which calculations indicate would give a capture velocity of approximately 0.17 mm/s. In order to achieve a capture velocity of 0.12 mm/s, the flow rate through the tube settler would have to be approximately 1.4 mL/s.

The PID system was also found to be performing appropriately. Experiments were run with a target turbidity of 50 NTU, and the turbidity was consistently held within ± 10 % (45 and 55 NTU) for extended periods of time. One issue that arose was a communication error between the influent turbidimeter and the interface. This could lead to problems with PID control, because when the two were dwasconnected, it gave a turbidity reading of -999. The PID system interprets this as a very low turbidity and responds by increasing the flow rate of clay. An alternate code was written for the turbidimeter so that the communication would need to fail (recieve a value of -999) 50 times before the -999 value was recieved by the system and interpreted as a low turbidity value. Until the communication failed 50 times, the value recieved before the -999 was read and reused as the influent turbidity value.

Performance Testing

The system was set to run through various PACl dosages in order to determine how the coagulant dose corresponds to the performance of the system in terms of turbidity removal. The coagulant concentrations being tested were 10, 20, 40, 80 and 160 μM as Al. These were equivalent to PACl concentrations of 1.05, 2.1, 4.2, 8.4, and 16.9 mg/L. For each dosage, the turbid water was run through the flocculator and then through the tube settler in order to test for successful flocculation and settling. All tests were run with an influent turbidity of 50 NTU.

It was initially believed that running the experiment continuously without backwashing would not affect the data, as the flocs would settle out of the tube and not interfere with the turbidity readings obtained from the next PACl dosage. However, experimental data demonstrated that residual turbidity rose as the experiment progressed, even though the PACl dosage increased. It was hypothesized that this rising turbidity was due to flocs settling at the bottom of the tube settler and being pushed back up from the pulsing of the peristalitic pump. Several actions were taken to combat this wassue: 1) A flow accumulator was added between the peristaltic pump and the tube settler to absorb the uneven flow 2) The system was backwashed after each PACl dosage to remove the residual flocs from the tube settler and 3) A state in which only water flows through the tube settler to remove flocs stuck at the bottom of the tube was implemented. These changes appeared to help mitigate the increasing residual turbidity, but as more experimentation was done it appeared that the backwash system that was in place was likely not sufficient for necessary cleaning. Further, it was later determined that the trend of increasing effluent turbidity with increased PACl dosage was observed regardless of the order of experimentation or the amount of backwashing that was done.

The backwash and water flow states caused the influent turbidity to drop, so when the loading state for the next PACl dosage began, the PID controller responded with a high flow rate, which caused a spike in the initial influent turbidity for each run. In order to combat this, the length of the loading stage was increased so that it was much greater than the residence time of the flocculator. This length was initially 25 minutes, and the flocculator was seen to achieve much better performance with much smaller turbidity spikes when the time was increased to 35 minutes. Notably, however, when experiments were run manually with a lengthy backwashing process in between, a loading time of only 25 minutes was used again and only minimal if any initial spikes in effluent turbidity were seen.

The ultimate goal of these experiments was to confirm that SWaT recieves similar results to those found with FReTA.

Results

Initial experiments were run on the laminar tube flocculator multiple times at varying PACl dosages. All of the doses were able to significantly reduce the turbidity of the water, with all of them bringing an influent of 50 NTU down to below 3 NTU once the performance became steady. These experiments were automatic and sequential, cycling through the five states described above and the five different PACl doses that were being tested in order of increasing concentration.

One factor of this experiment that was been slightly problematic was that high initial turbidities were repeatedly observed, likely as a result of the clay dosing system. Using the PID system, the influent turbidity spiked largely every time the system transitioned back into the loading state after backwash. Although it was only temporary, the influent turbidity would up to as high as 650 NTU and this seemed to be interfering with the experimental results. All of the dosages showed a somewhat higher effluent turbidity at the beginning of the SWaT state, which was likely a result of this initial influx of high turbidity. The loading state was initially 25 minutes long to try and account for this, but that length was probably not sufficient. When the loading time was increased to 35 minutes, the results improved significantly, although there were still some issues with higher effluent turbidities at higher PACl dosages. It was also apparent that the runs with higher PACl dosages take a much longer time to reach acceptable effluent turbidity levels after the initial spike. It was unclear whether this was entirely a result of the initial spike in influent turbidity, or if this initially high effluent value was simply a part of the process with the SWaT system.

Figures 2 and 3 show effluent turbidities for all PACl dosages for an initial experiment in which the loading time was only 25 minutes long. The first figure was the data for the entire SWaT state, while the second shows the data only after the system had already been in the SWaT state for approximately 12 minutes, by which time the effluent turbidities for all of the runs seem to have settled out at a relatively stable value.

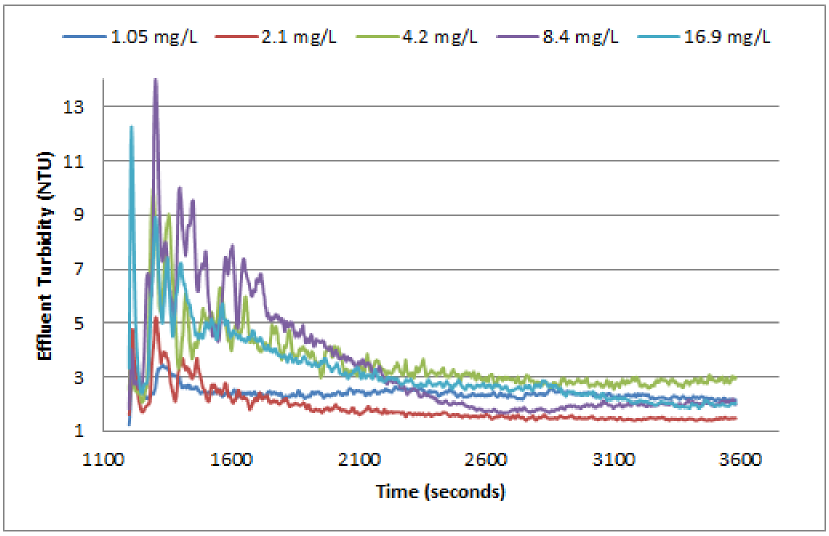

Figure 2: Effluent turbidity for all PACl doses during SWaT. Data was from an initial experiment in which the loading time was only 25 minutes long and capture velocity was 0.17 mm/s.

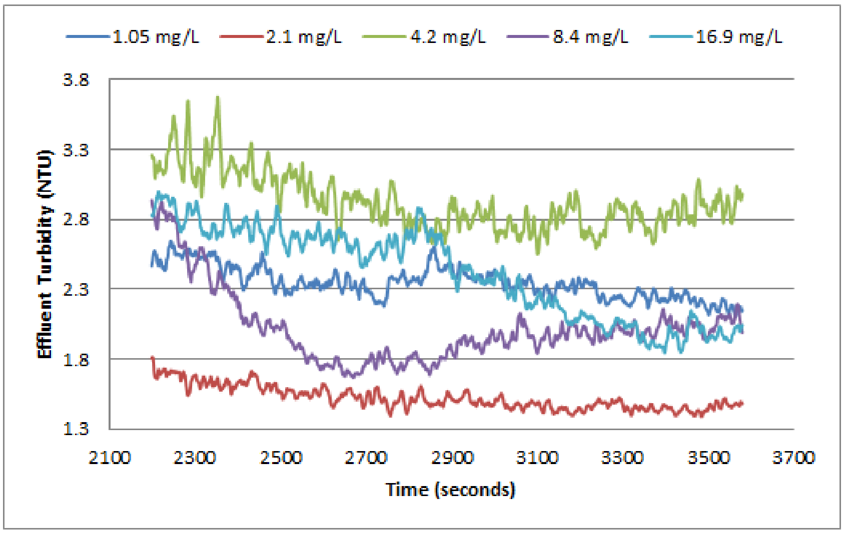

Figure 3: Effluent turbidity for all PACl doses after 700 seconds in SWaT, at which point all effluent turbidities appear to have settled at a relatively steady value. Data was from an initial experiment in which the loading time was only 25 minutes long and capture velocity was 0.17 mm/s.

The results that were obtained after the loading time was increased to 35 minutes showed a significant improvement in flocculator performance, and the effluent turbidities for all of the PACl dosages were noticeably lower. It was again clear that the higher PACl doses took longer to reach a low and steady effluent turbidity, and they also experienced higher initial spikes in turbidity despite the increased loading time. This can be seen in Figure 4, which shows the effluent turbidities for all PACl dosages throughout the SWaT state. Figure 5 shows effluent turbidities for all PACl dosages after approximately 13 minutes in SWaT, at which point all effluent turbidities appear to have settled down to their lowest values. As can be seen from the figures, this optimal performance continues for over 25 minutes. At this point, the system would have automatically transitioned into backwash, but it appears that it could have continued to run effectively for a longer time if it had been left in the SWaT state.

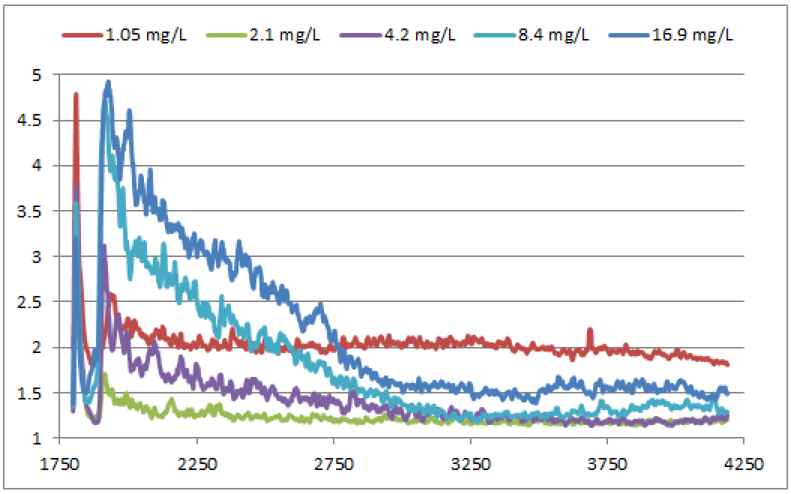

Figure 4: Effluent turbidity for all PACl doses during SWaT. Data was from an experiment in which loading time was 35 minutes and capture velocity was 0.17 mm/s.

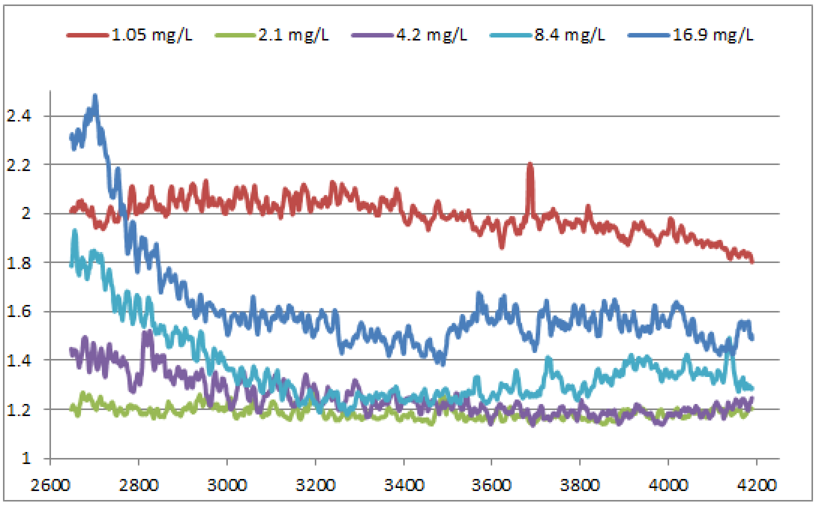

Figure 5: Effluent turbidity for all PACl doses after 800 seconds in SWaT, at which point all effluent turbidities appear to have settled at a relatively stable value. Data was from an experiment in which loading time was 35 minutes and capture velocity was 0.17 mm/s.

The results from the initial experiments were somewhat different than what was expected, because the performance did not improve with increasing PACl dosages. In previous experiments performed by Kweren Swetland using FReTA, there was a clear trend for all influent turbidities and residence times that the turbidity removal improved with increasing PACl dosages. However, as shown in Figure 6, there was no such trend to be seen so far in these results. The graph shows pC*, which was a measure of turbidity removal equal to $-log(\frac{C_{effluent}}{C_{influent}})$, in which C is the concentration of clay in the water. The figure compares the average effluent during optimal performance of the flocculator with an influent turbidity of 50 NTU.

There were several possible reasons why the results obtained here might have been different than those that were previously obtained using FReTA. One was that it could be related to the PID problem that was described earlier, which caused each run of the experiment to recieve a brief influx of very high turbidity water when the system transitioned. This problem seemed to have had a greater effect on the higher PACl dosages, as the resulting high initial effluent turbidities appeared to be much higher for the PACl doses of 8.4 and 16.9 mg/L. This could have caused problems throughout the experiment, because these dosages also took a longer time to reach a steady and low effluent turbidity. It could also have contributed to floc buildup at the bottom of the tube settler, which was observed to be occurring primarily for the two higher PACl dosages.

It was also possible that this floc buildup was a problem with the SWaT system in general. It could have been the case that the physical setup of the system simply dd not allow flocs to drain out and escape the tube settler easily enough, and this might have had a more significant impact at the higher PACl dosages. If there was floc buildup at the bottom of the tube settler, it could be causing floc breakup or recirculation at a time when it was not ideal, which could have allowed for the creation of more small particles that were able to pass all the way through the tube settler.

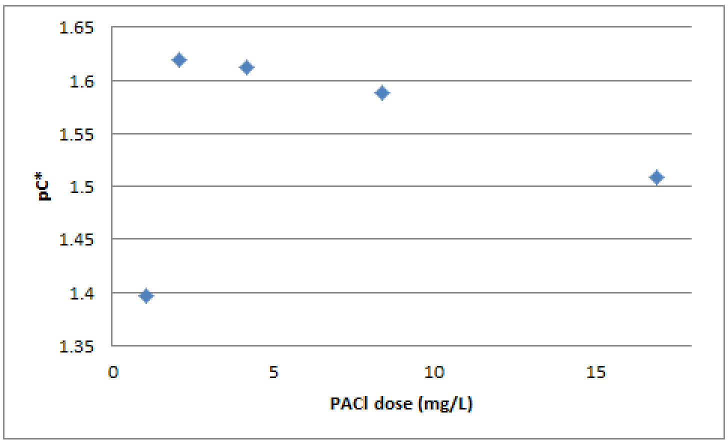

Figure 6: pC* for all PACl doses, based on performance after reaching steady effluent turbidity values. Data was based on experimentation after the loading time was increased to 35 minutes, at which point peak performance of the flocculator was achieved.

Performance at High PACl Dosages

Because the decrease in performance for increased PACl dosages was rather unexpected, steps were taken to investigate what might have been the cause of that result. One possibility was that it was simply a result of these higher dosages having been run later in the cycle, and if the backwashing was not completely effective, then that could have led to decreased overall performance as the system continued to run. In particular, it was possible that this was causing problems at the highest PACl dosage (16.9 mg/L), because the backwashing process might not have been cleaning the tube settler effectively enough before transitioning into this final stage of the experiment. For both the 8.4 mg/L and the 16.9 mg/L PACl dosage, significant build-up of flocs at the bottom of the tube settler had been observed, and particularly for the 8.4 mg/L dosage it had also been observed that these flocs could be difficult to remove during backwash.

Another possibility was that the physical setup of the system and the geometry at the inlet of the tube settler were such that the flocs were not able to settle out, which could have led to issues in the tube settler if flocs were being resuspended or if there was unwanted floc breakup upon entering the tube settler. In order to test these potential sources of error, experimentation was done on the two highest PACl dosages by simply running the flocculator in SWaT at those two dosages without cycling through an entire experiment.

Figure 7 shows effluent turbidities for the two highest dosages when these were run without having cycled through the entire experiment. For both dosages, it was still apparent that the floc buildup was occuring at the bottom of the tube settler. Upon observation, it was difficult to determine whether or not this included recirculation happening at the bottom of the tube settler as a result of the inflow of water into the tube. However, particularly for the 8.4 mg/L dosage, it appeared as though there was possbily some floc breakup occurring that was allowing smaller flocs to form and travel further up the tube settler. For the 16.9 mg/L dosage in particular, performance was significantly better than anything that had been previously observed, not only for this dosage but for all PACl dosages.

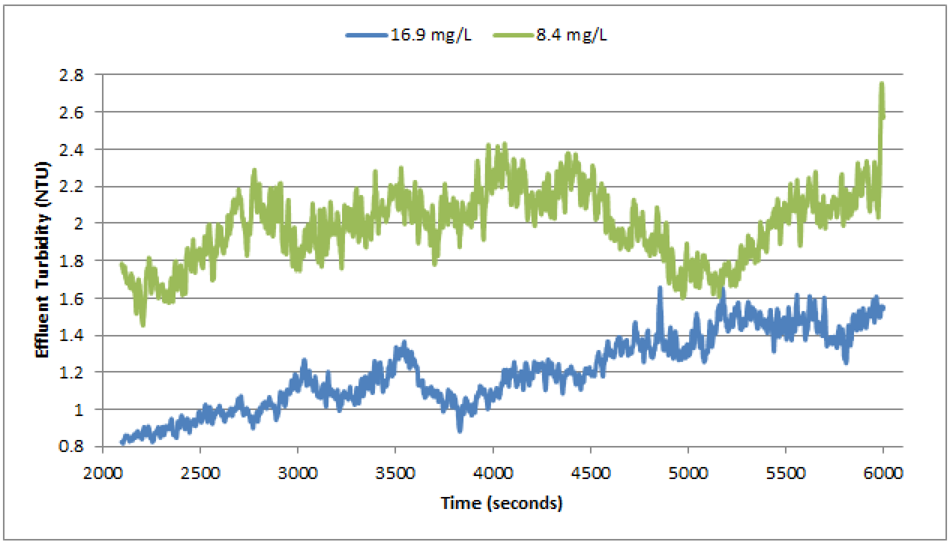

Figure 7: Effluent turbidities during optimal performance in SWaT for PACl dosages of 8.4 mg/L and 16.9 mg/L. The higher PACl dosage was run first, without having cycled through the rest of the experiment, and significantly better performance was observed despite still seeing a buildup of flocs at the bottom of the tube settler.

Manual Testing and Comparisons to FReTA

After the above tests at the higher dosages were run, the team decided to do manual testing of all of the doses in order to be able to compare them while also being able to fully control the amount of backwashing that was occurring and monitor the system at all phases of each experiment. For these tests, the flow rate through the tube settler was also reduced in order to achieve a capture velocity of 0.12 mm/s. Significant improvement in performance was seen for all of the PACl dosages once the capture velocity was thus reduced, as smaller particles now had sufficient time to settle out in the tube before passing out of the system. A similar trend was seen in these experiments as in the previous ones, with optimal performance being achieved at one of the middle PACl dosages and performance declining as the concentration increased to the highest dosage. As can be seen in Figures 8 and 9, this is drastically different from what was observed with FReTA. As shown below, in Karen Swetland's data, there was a very clear trend of increasing performance with increasing PACl concentration, while experimentation with SWaT has repeatedly resulted in optimal performance being achieved at one of the middle PACl dosages.

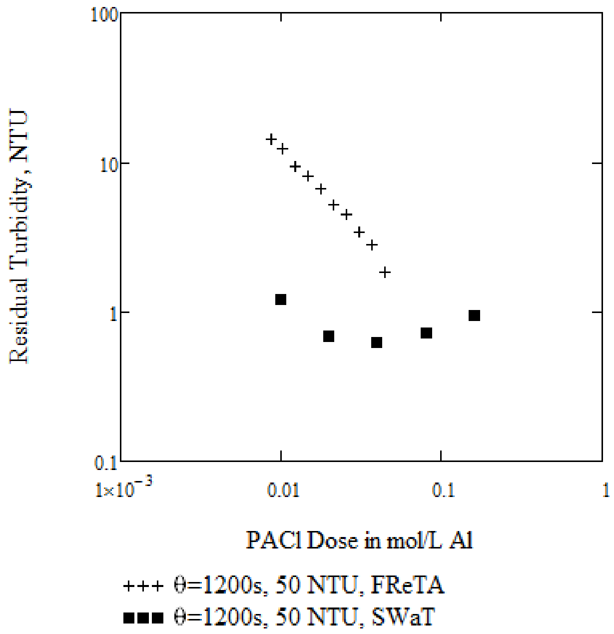

Figure 8: Residual turbidity values for various PACl dosages in both FReTA (Karen Swetland's data) and SWaT. For both systems, the capture velocity was 0.12 mm/s.

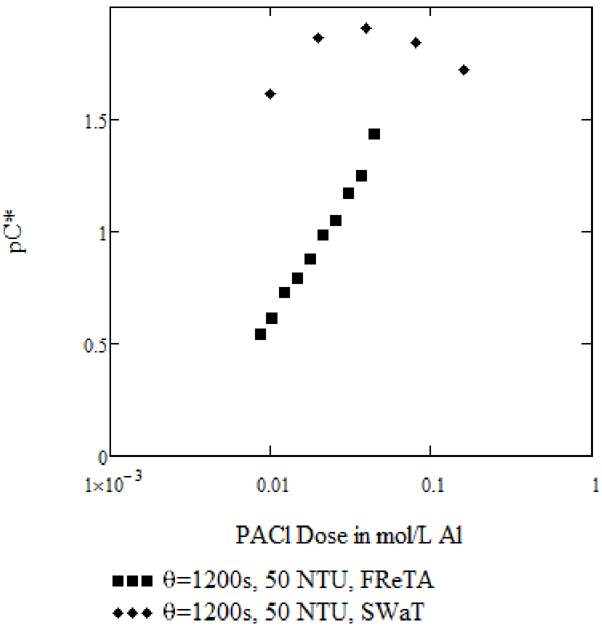

Figure 9: pC* values for various PACl dosages in both FReTA (Karen Swetland's data) and SWaT. For both systems, the capture velocity was 0.12 mm/s.

There are several observations that were made during this manual experimentation comparing the different PACl dosages. First, for these experiments, the loading time used was only 25 minutes, but there were no major spikes in initial effluent turbidity seen for any of the doses. This indicates that the earlier problem had in some way been the result of the sequential system of experimentation that had been set up.

Another interesting observation is that the flocs formed for the PACl dosages of 2.1 mg/L and 4.2 mg/L actually appeared to be larger when they were observed draining from the system than did those flocs that formed for the PACl dosages of 8.4 mg/L and 16.9 mg/L. Further, at the two best-performing doses, it appeard that the flocs barely flowed up into the tube settler before they settled out and flowed from the system through the drainage tube. Alternatively, for the two higher doses, it was evident that there was still greater floc buildup, and a more noticeable amount of flocs was reaching a higher level in the tube settler before actually settling down in the tube.

As can be seen in the above figures, the performance thus far observed with the SWaT system not only does not follow the same trend as the earlier data, but it has actually resulted in significantly lower residual turbidities. This is an indication that this data does not fit within the the previous model, which had been developed to fit the data from previous experimentation using SWaT, but is actually performing significantly better than the model would have predicted for all PACl dosages.

Future Work

As the results from performance testing of the SWaT system are thus far somewhat inconclusive, it appears as though more experimentation will need to be done in order to determine how this system compares to FReTA and how its results fit into the flocculation model that was hypothesized by Karen Swetland. In order to accurately compare data from the two systems, further testing should be done on SWaT with a capture velocity of 0.12 mm/s. It is also important to do further experimentation in order to determine why these results have thus far shown declining performance at higher PACl concentrations.

After further experimentation has been completed to compare SWaT with FReTA, testing should be done on the system that incorporates tapered flocculation and floc breakup. For these experiments, the head loss through the flocculator will be significantly increased by the addition of needle valves throughout the tubing. When closed, these needle valves will lead to greater energy dissipation through the flocculator, and tests will be run to determine how this floc breakup affects flocculation and settling. These experiments will be run with PACl dosages of 4 mg/L as Al, an influent turbidity of 150 NTU, and target head losses of 1, 2, 4, 8, 16, and 32 cm, which will be achieved by closing an increasing number of valves in the system.

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