Laminar Tube Flocculator Team

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Abstract

Flocculators are an integral part of the water treatment process. The flocculation process turns the colloidal matter within water into flocs that will eventually be removed through the sedimentation process. The creation and eventual settling of flocs formed in the flocculator results in cleaner, clearer water. According to Swetland et al.'s[**?**]hypothesis, flocs that reach a certain size are no longer effective in removing colloids because the shear on the surface of the flocs becomes too high for the colloids to attach. Thus, by breaking large flocs, they may regrow and scavenge additional small colloids that were not able to settle out from the suspension. The purpose of this series of experiments is to continue testing the Floc Breakup Theory and, if valid, to determine the most effective way to break up flocs in order to have the highest removal rate of colloidal particles. The settled water turbidity analyzer (SWaT), a new turbidity measurement system, was designed and implemented for the Spring 2014 research, in which the effluent water first travels through an angled tube settler with continuous flow before being analyzed by the effluent turbidimeter. A base case test was run to serve as a control showing residual turbidity with the new turbidity measurement system. Adjustments to the new setup were made to accommodate for issues that arose from the new turbidity measurement system.

Part I

Introduction

In the process of treating drinking water, flocculation is used to decrease the turbidity of influent water. To do so, flocculators are used to facilitate collisions between suspended particles. In the presence of a coagulant, the colliding particles agglomerate to form flocs. The sedimentation of these flocs results in a decrease in the residual turbidity of the water being treated. Even though the technology for flocculation has been used for decades, the process of floc formation is still not completely understood. The purpose of our research on the laminar tube flocculator is to further the understanding of the flocculation mechanisms by extending the work of previous groups and to test Swetland et al.'s (2012)[?] hypothesis that large flocs are not effective in removing colloids. Preliminary results from Summer 2013 research indicated that having constrictions on the tube flocculator to create zones of high energy dissipation was effective in breaking up flocs. However, the Fall 2013 research had results that both refuted and supported the idea that breaking flocs was effective in lowering the overall residual turbidity of the water. Using these results as an initial start, the experiments performed this spring semester will consist of a base case and experiments that test different sizes of flow constrictions. The base case test will dictate the optimal coagulant dosage to be used in the variable experiments, and will be a control set of results that can be used for comparison and data analysis.

The goal of the Laminar Tube Floc team this semester is to prove whether using clamps to constrict the flow will assist in lowering the residual turbidity of the water leaving the plant and improve flocculator performance by using a new turbidimeter design called the Settled Water Turbidity measurement system (SWaT). If residual turbidity does decrease due to floc break up, then the Laminar Tube Floc team can integrate floc break up into the flocculation process to create a more efficient design for the flocculator in the AguaClara water treatment plant. However, if the floc breakup theory is proven wrong and residual turbidity increases due to floc break up, then an alternate hypothesis must be offered to explain the reduction in efficiency of the flocculation. Although past group's work have shown that clamps are useful in breaking up flocs and lowering residual turbidity, we want to perform a set of experiments that have replicable results, providing enough significant data to draw strong conclusions.

Part II

Literature Review

Current design guidelines for flocculators are based on empiricism, but it is widely known that floc size is directly correlated with the energy dissipation rate [?, ?]. In laminar flow, energy dissipation rate and the velocity gradient can be related as follows [?]:

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

where G = velocity gradient, ε = energy dissipation rate, and ν = kinematic viscosity of water.

equation (1) describes a proportional relationship between the velocity gradient and dissipation rate. It is anticipated that under laminar conditions, a high enough velocity gradient must be used to prevent flocs from settling prematurely and to evenly distribute the coagulant precipitates onto the colloids in the influent water. The velocity gradient, however, still has to be low enough to avoid too much shear, which causes flocs to disperse into colloids [?]. Due to the presence of laminar flow in our experimental flocculator system, the parameter

G is valid for the model [?]. The coiled configuration of the tubing can also be regarded as an arbitrary flow reactor with a high Peclet number, meaning it can be assumed that as a particle travels through the tubing, particles of the same size collide and floc size increases [?].

Swetland et al. (2012) [?], developed a predictive model for residual turbidity as a function of conditions in the flocculator (shear, and hydraulic residence time), the influent turbidity (qualified as floc volume fraction) and surface coverage of colloids by the coagulant [?]:

$$C* = (\frac{1}{\beta G \vartheta \Gamma \Phi})^{\frac{2}{3}}$$

where C* = residual settled water turbidity divided by influent turbidity, G = average velocity gradient, β = coefficient equal to 10^b(b is the y-intercept found from plotting the pC* experimental data vs. $\log(G\vartheta\Gamma\Phi^{\frac{2}{3}})$), ϑ = hydraulic residence time, Γ = fractional coverage of colloids by coagulant, and Φ = floc volume ratio.

II shows how a higher energy dissipation rate (as related to the velocity gradient by equation (1)) results in higher removal of clay particles. However, too high of an energy dissipation rate, as mentioned above, is expected to result in unwanted break-up of the flocs, not allowing them to grow enough to settle out. Therefore, it is very important to design flocculators to maintain the optimal energy dissipation rate and control the floc sizes formed.

The most efficient fluid shear levels for optimal removal of turbidity are still not clearly understood. Fluid shear levels, measured as the average energy dissipation rate ε, that will produce the "best" flocs (qualified as the size most effective for colloid removal) are evaluated by measurements of the residual turbidity of water leaving the flocculator. Theoretically, having a high energy dissipation rate would increase the collision frequency occurring between the flocs and create larger flocs. However, having a high energy dissipation rate would also mean that there would be more breakup of large flocs; the larger the flocs become, the more susceptible they are to breakup.

Swetland et al. [?] experimented with a range of influent turbidities from 5 NTU to 500 NTU and found the most effective percent removal occurred in the range of 50 to 150 NTU. Influent turbidities outside this range, both higher and lower, performed poorly, due to the hypothesized factors of fractional coverage of clay by coagulant and inadequate floc volume fraction. The Fall 2013 Laminar Tube Flocculator team's research showed that the 4 mm clamp was not effective in lowering the residual turbidity of the water in comparison to the base case. However, the 5 mm clamp did lower the overall residual turbidity of the water by about 0.2 NTU for a PACl dosage of 0.8 mg/L and by about 0.25 NTU for a PACl dosage of 1.8 mg/L. The data for the 5 mm clamp did not show significant correlations to the base case since the p-value for that set of data was greater than 0.05 so this experiment could not serve as sufficient evidence to support the Floc Breakup Theory; the results from Fall 2013 can be seen in figure 1 below.

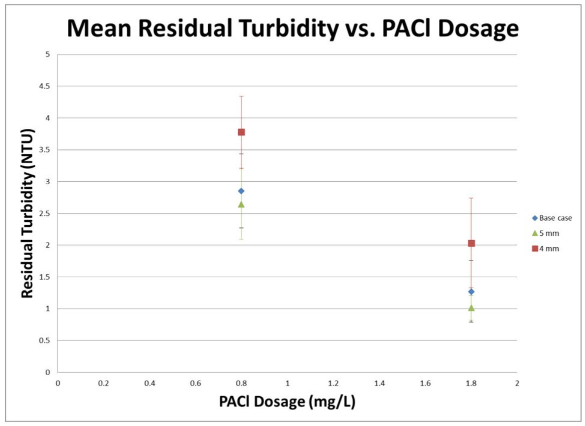

Figure 1: Fall 2013 Research

The number of particle collisions per unit time in a laminar flow flocculator is proportional to G and the time available for collision is ϑ. The parameter $G\vartheta$ indicates the degree of flocculation that can be achieved. Generally, floc sedimentation velocities increase with $G\vartheta$ because flocs will grow in size when they are given more time (a larger ϑ) to flocculate. However, in Ian Tse's studies [?], he found that floc size did not really increase once $G\vartheta$ values were greater than 15,000 and flocculation time continued to increase. The figure-eight experimental flocculator shape was adopted based on the suggested $G\vartheta$ value of about 20,000 when dealing with larger scale floc formation [?]. The point past $G\vartheta$ values of 15,000 is where the flocs have reached a condition in which they are at a size limited by breakup. High fluid shear levels will hinder the flocs from growing in size at high G values. From the results of Ian Tse's study [?], it can be concluded that quick-settling flocs and low turbidity effluent are best produced when the energy dissipation rates are low.

Part III

Methods

1 PACl and Clay Preparation

PACl was obtained from the Cornell Water Treatment Plant in aqueous form and diluted to stock solutions of 60 g/L and 15.5 g/L by Casey Garland. We prepared our PACl dosage for the initial base case by diluting the stock solution in the Water Treatment Lab to 100 mg/L using deionized water. The stock solution was diluted to 60 mg/L for the clamp size testing. The kaolin clay stock suspension was kept at a concentration of 10 g of clay per liter of tap water and

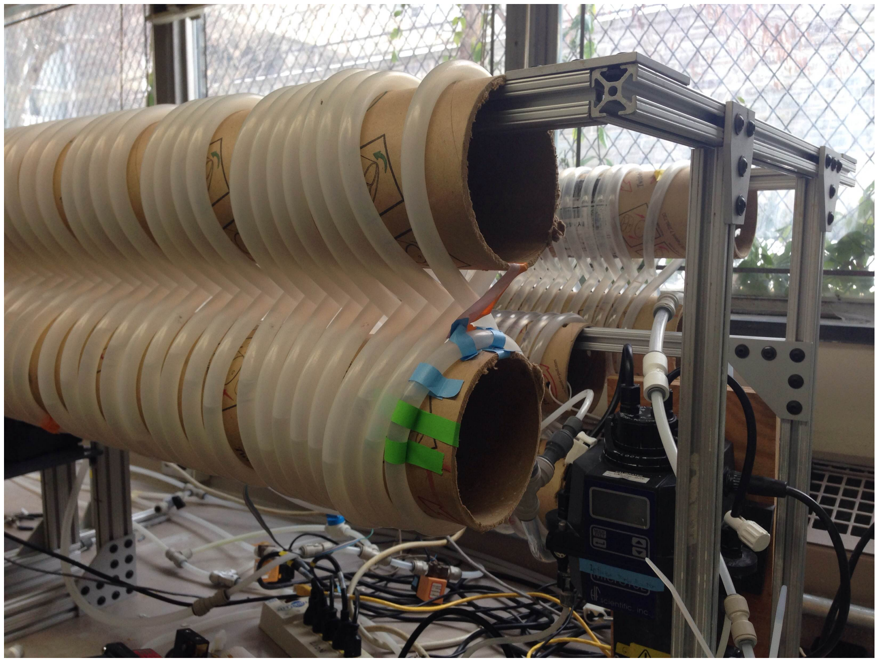

Figure 2: Coil Tube Arrangements

was used to maintain the synthetic raw water (SRW) influent turbidity at 100 NTU.

The influent SRW (synthetic raw water) to the system is kept at 100 NTU by a pinch-valve deposit configuration. The clay/water suspension was added to a SRW reservoir that has a connection to both an influent turbidimeter and to a MasterFlex pump. The turbidity of the influent and effluent water are measured by turbidimeters. Process controller software maintained the influent turbidity at the desired influent level of 100 NTU by adding clay suspension to the SRW when it was detected that the turbidity dropped below the desired value.

2 Flocculator Setup

The laminar tube flocculator consists of three coiled 1/2" tube arrangements connected in series. The total tubing length used was 83 m; one 23 m long silicone tubing arrangement is attached in between two 30 m long Tygon tubing arrangements. All three arrangements of tubing are wrapped around two 11 cm outer diameter parallel cardboard tubes in a figure eight shape. Having the tubing wound up in a figure eight shape reduces the effects of flocs settling on the sides of the flocculator by alternating the orientation of the velocity gradient. The cardboard tubes are used for structural support.

Silicone tubing was chosen to be the middle segment used for experimentation due to its elasticity, which allows it to quickly reform to its original shape after clamps are removed. The research group from the summer discovered that "dents" were left on the Tygon tubing once clamps were removed. These dents acted as "clamps" since the cross sectional area for regions that had dents was smaller than the cross sectional area for regions without dents. Thus, the flocs would speed up when entering regions where dents were left. To prevent this from occurring, we decided to arrange the silicone tubing so that it would be in the middle of the three groups of tubing and to restrict application of clamps to the region of silicone tubing.

A differential pressure sensor is attached at both the beginning and end of the second arrangement of tubing. This sensor measures the difference in pressure before the flocs go through the clamped section of the flocculator and the pressure after the flocs have gone through the clamped silicone tubing arrangement. This difference in pressure monitors the pressure drop, or head loss, across the flocculator due to the clamps causing more flow expansions within the flocculator. In a previous setup where the tubes attached to the pressure sensor were pointing downward, flocs were settling onto the tubes on both sides of the differential pressure sensor, possibly affecting the pressure data collected. To fix this problem, the attached tubes were adjusted so that they point upward at the point of attachment to the silicone flocculator tubes, preventing flocs from traveling down into the pressure sensor tubing.

3 SWaT System

To gain more accurate results for the effluent turbidity readings for our experimental data, we used the Settled Water Turbidity (SWaT) analyzer rather than the Flocculation Residual Turbidity Analyzer (FReTA). SWaT is a measurement apparatus that is capable of measuring floc sedimentation velocity without physically affecting the flocs that are formed within the flocculator. The previous turbidimeter system, FReTA, used in Fall 2013 and years before, was not providing accurate, precise data. Data points fluctuated significantly at PACl dosages above 2 mg/L, and our conclusions were that FReTA was having problems accurately measuring the turbidity due to the recirculation of flocs within the glass column. The SWaT set up was designed to model the water treatment plants used in Honduras, thereby providing residual turbidity readings over a continuous period of time that could result from a real AguaClara plant.

SWaT is composed of a tube settler that leads to a turbidimeter (figure 4). The tube settler is a 1 inch diameter PVC pipe set at an angle of 60 degrees and is 1.04 m long, preventing floc roll-up and allowing for a capture velocity range of .1 mm/s to .5 mm/s. The system is designed so that 90% of the effluent water from the flocculator is directed through the tube settler and 10% is directed to waste flow. The waste flow also serves to carry out any buildup of flocs at the bottom of the tube settler. The flow rate through the tube settler is controlled

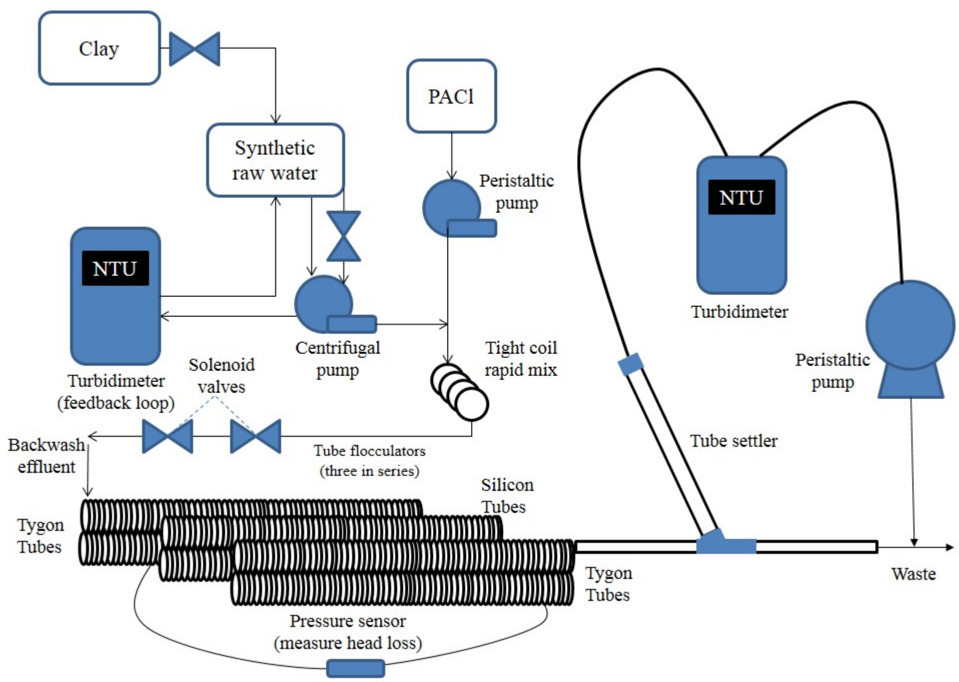

Figure 3: Full flocculator setup

Parameter	Value
Length	1.04 m
Inner Diameter	26.65 mm
Angle	60 degrees
Flow Rate	5 mL/s
Capture Velocity	0.5 mm/s

Table 1: Parameters of the Tube Settler

by a peristaltic pump that is linked to the setup after the turbidimeter.

The length of the tube settler was calculated by solving the following flow rate equation 2 for the length:

$$Q_{Tube} = A_{Tube}\frac{V_{Capture}(L_{Tube}sin(\alpha)cos(\alpha) + D_{Tube})}{D_{Tube}} \tag{2}$$

By using the specification that 90% of the effluent water will be directed to the tube settler, and rounding up for convenience, the tube settler flow rate was set to 5 mL/s. A critical capture velocity of 0.5 mm/s was used. Using these values, the length was solved in 3:

$$L_{Tube} = \frac{D_{Tube}(Q_{Tube} - A_{Tube}V_{Capture})}{A_{Tube}V_{Capture}cos(\alpha)sin(\alpha)} = 1.04m \tag{3}$$

With this length for the tube settler, the residence time of the tube settler is 9.68 min.

The method in Process Controller was revised to accommodate for this new SWaT setup. Only three states exist now: Backwash, Loading State, and SWaT. In Backwash, the apparatus is cleaned by highly pressurized water flow in the reverse direction of experimentation. In the Loading State, PACl is added, if needed for that run, and continues in this state for 36.3 minutes to allow a sufficient amount of flocs to form and to allow for the water to travel through the entire flocculator and tube settler system. After the Loading State, the SWaT state runs, which is when the effluent turbidity of the water after the tube settler is recorded. This state lasts for 30 minutes and the data collected during this time is what is analyzed from the experiments.

Part IV
Experiments

Our first experiment for the base case resulted in turbidities higher than the desired value of 5 NTU or below. For a PACl concentration of 1 mg/L, the average effluent turbidimeter reading was around 20 NTU, which is much higher than the effluent turbidity readings from previous experiments with the FReTa system. Some errors that occurred during our experiments were that backwash

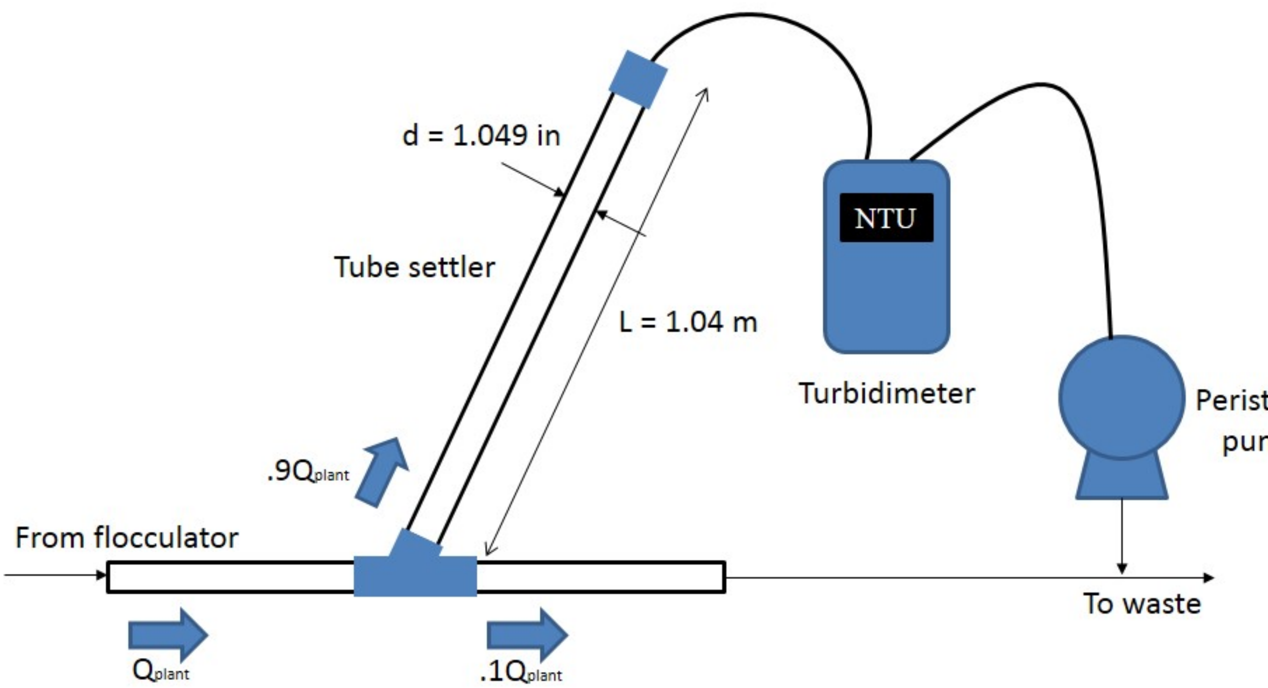

Figure 4: Detailed SWaT setup diagram

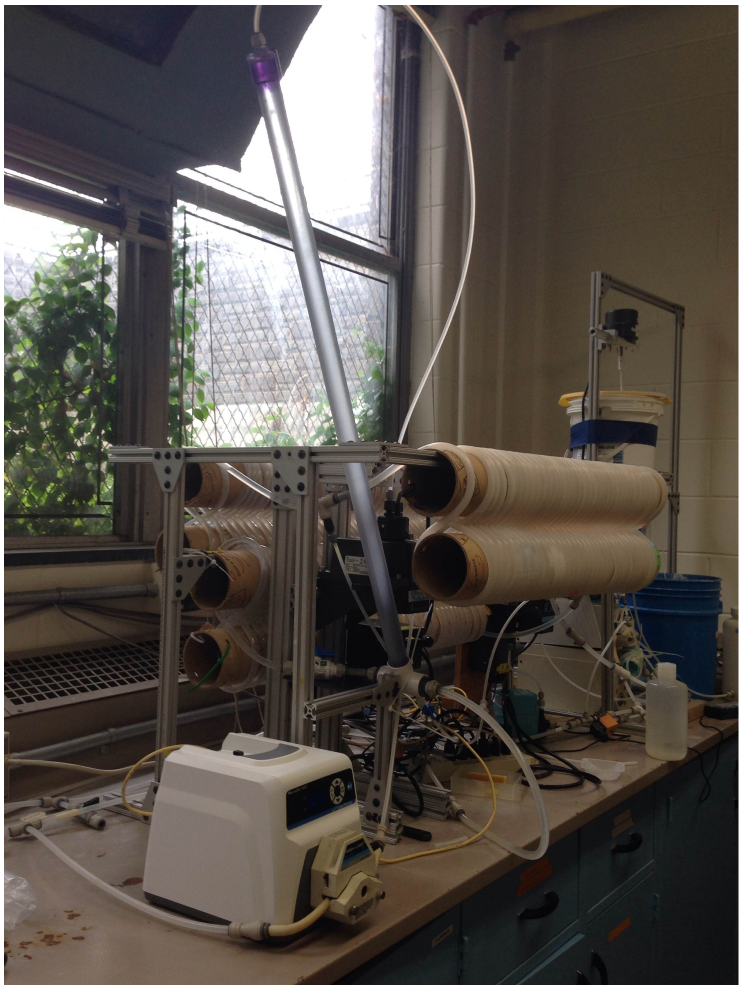

Figure 5: SWAT System Design

was not sufficient in cleaning the tube settler and Process Controller dosed at four concentrations of 0 mg/L, 1 mg/L, 2 mg/L, and 3 mg/L even though the method file only programs for three dosages. The new SWaT system still needs a lot of improvement and work to be able to produce accurate, consistent data.

Similar problems with the SWaT system arose as with the FReTA system: the effluent water dropped to around 70 NTU at the start of the experiment when no PACl had been added into the flocculator system even though the turbidity of the influent water was 100 NTU. Last semester, we had concluded that there was left over PACl in the flocculator after each run of the experiment which caused the effluent turbidity to drop after the water had traveled through the entire system. This same problem seems to be occurring with the new turbidimeter system as well. A ball valve was installed prior to the tube settler so that it could be manually closed during backwash to be able to send a sponge through the tubing at a higher water pressure. With a higher water pressure, the tube flocculator should be cleaned more efficiently. The experiments using the new turbidimeter apparatus resulted in residual turbidity readings higher than the Fall 2013 experiments. Last semester at a PACl dosage of 0.8 mg/L, the turbidity readings dropped to a range of 2 to 4 NTU. However, with the SWaT system, we are seeing effluent turbidity readings of around 20 NTU after 1 mg/L of PACl had been added into the system.

Part V

Results and Conclusions

A problem with our initial SWaT setup was that there was no outlet for the flocs within the Tube Settler to exit and that the residual turbidity of the effluent water was higher than the influent water from the FReTA setup. The effluent water surpassing the tube settler was supposed to function by collecting and carrying away the buildup of settled flocs at the bottom of the tube settler into the waste stream on the other side of the T-joint. However, because the old design had an elongated tubing connection from the T-joint to the tube settler, there was no direct exit route for the flocs at the bottom tube settler to be carried away by the waste stream, resulting in all the flocs accumulating and recirculating within the tube settler (figure 9). This caused the residual turbidity to remain consistently at around 60 NTU after the loading state and to shoot up to over 100 NTU in the last two runs of the experiments during the backwash state. The effluent water's turbidity was significantly above the influent water's turbidity at times because all the flocs that had been accumulating within the tube settler traveled all the way through the tube settler and sent through the effluent turbidimeter, resulting in higher NTU values than would occur if the tube settler had a route to waste for settled flocs. The effluent water of the initial SWaT system was consistently higher than the target residual turbidity of 5 NTU and at times was even higher than the turbidity of the influent water going into the system.

Another discovery we made after this base case experiment was that backwash alone was not sufficient enough in cleaning the tube settler after each run through the experiment. At the end of the experiment, the top of the tube settler (figure 8) was significantly dirtier than the bottom half of the tube settler (figure 7). The inlet flow of water was recirculating the flocs around the bottom half of the tube settler however, around the top half of the tube settler, the flocs were settling against the side of the tube settler and sticking there rather than rolling down and being recirculated again (figure 6). The cause of this problem was also due to the lack of a sufficient exit route for the flocs within the tube settler, causing the flocs produced to remain within the tube settler and continue to build up.

To provide the flocs with an exit route, we designed a new T-joint to connect to the bottom of the tube settler which would allow flocs to be carried away by the waste stream, while still sending water into the tube settler to cause recirculation of the floc blanket inside. This new design has a valve attached to the end of the T-joint nearest the tube flocculator. This design aspect was implemented to help with the "pigging" process so that a sponge could be sent through the flocculator tubing without getting stuck in the tube settler (figure 10). The new entrance and attachment from the flocculator to the tube settler is a 1" PVC Tee joint with a 1/2" reducing threaded bushing on either side of the straight part of the Tee. A threaded 1/2" push-to-connect is attached to each bushing, linking the flocculator to the waste stream. The tube settler is attached to the perpendicular tubing of the T-joint and the T-joint is angled at 60º. The tube settler was reoriented and attached to the framework of the flocculator setup with zip ties and fitted bar structures to ensure a sturdier setup, as opposed to the initial setup where the tube settler was simply resting on a bar to achieve the 60º angle.

The new data with the improved T-joint design showed similar trends with the data incorporating the initial T-joint design (figures 11 12). For one round of experiments, three dosages (0, 1, and 2 mg/L) were each tested two times. For an entire round of 0 mg/L, and half a round of 1 mg/L, the residual turbidity graphs for both base case tests resembled a square wave function. However, for half of the 1 mg/L test round and for the entire round of the 2 mg/L test, the residual turbidity shot to NTU values significantly higher than the influent turbidity readings.

Unfortunately, the data provided from our research this semester does not provide any supporting evidence to either refute or prove the Floc Breakup Theory. No conclusions can be made regarding whether or not breaking flocs in the middle of the flocculation process causes flocculation performance to improve or worsen. One conclusion that we can make thus far is that the SWaT system requires further understanding and improvement in order to accurately test the Floc Breakup Theory.

Figure 6: Tube Settler After First Experiment

Figure 7: Bottom Half of Tube Settler

Figure 8: Top Half of Tube Settler

Figure 9: Old Design

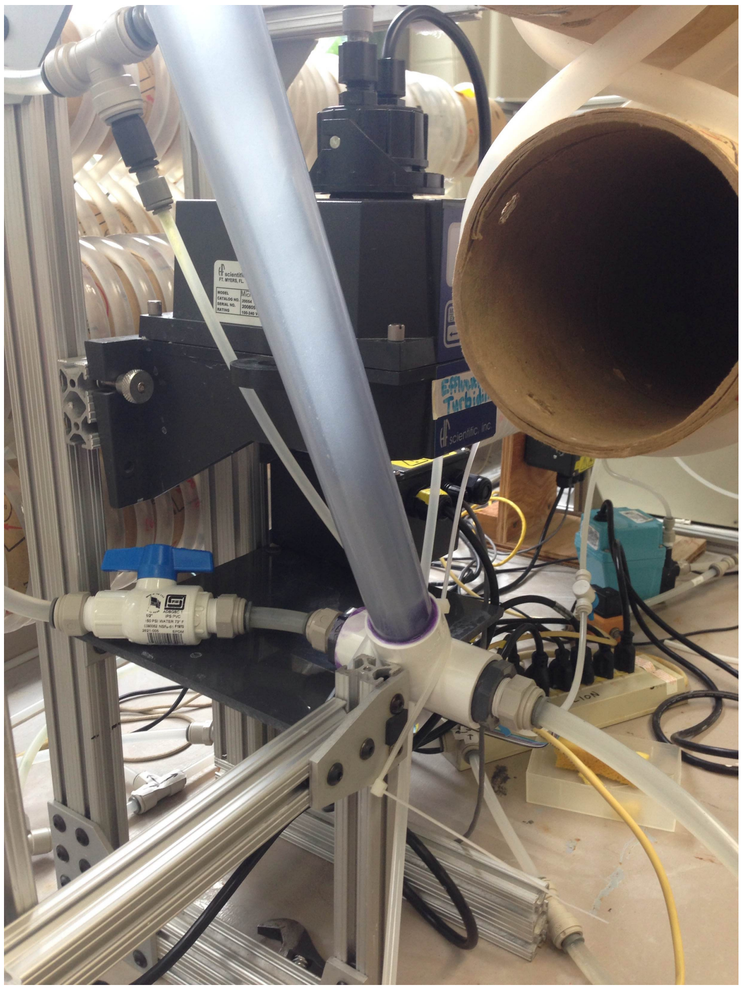

Figure 10: New Design

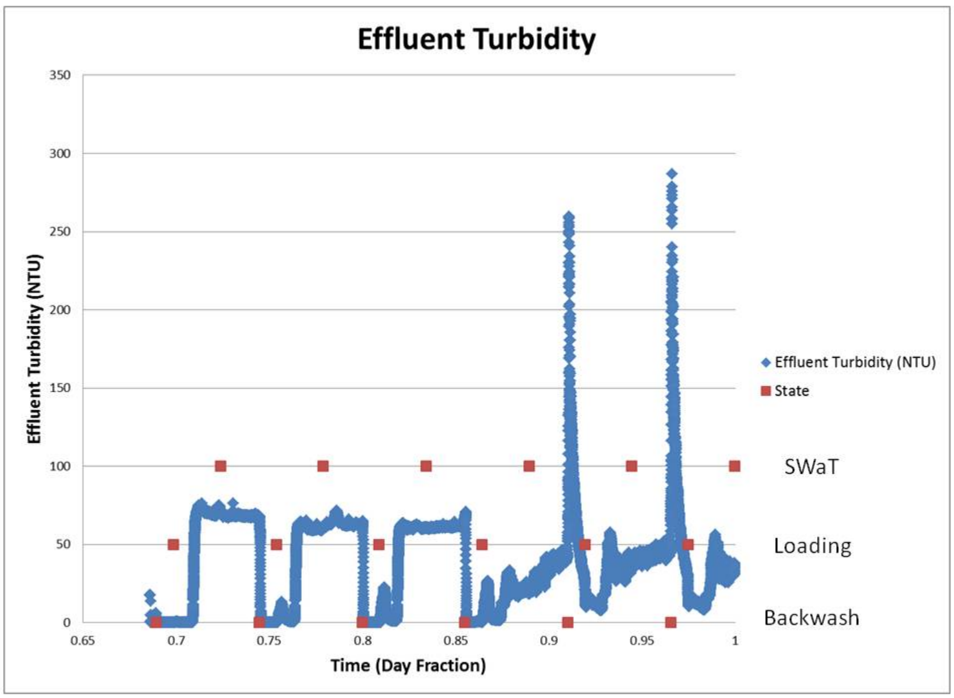

Figure 11: Base Case Data

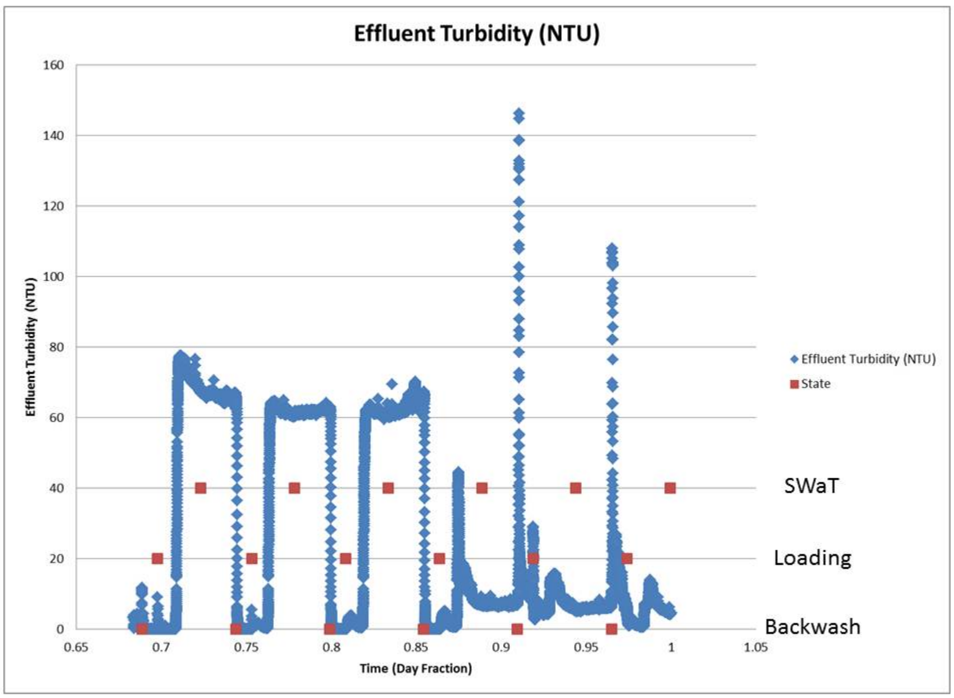

Figure 12: New Base Case Data

Part VI

Future Work

As previously mentioned, the SWaT system must first be understood and updated to resolve the extremely high effluent turbidity issue. Once the SWaT system is operating consistently and accurately, which can be evaluated through base case testing, experimentation with variables can be done. Future work for the Laminar Tube Flocculator team includes coming up with a conclusion for the Floc Breakup theory, doing clamp testing with different numbers of clamps ranging from two clamps to sixteen clamps, and possibly doing a tapered flocculator test in the case that the Floc Breakup theory is proven incorrect. If the evidence from future work done by the Laminar Tube Flocculator team refutes the Floc Breakup theory, then an alternative hypothesis as to why flocculation performance worsens with time must be offered. The Tapered Flocculation test would be designed with energy dissipation rates starting from 1000 mW/kg and the team would run multiple experiments testing the tapered system and its effects on residual turbidity.

References