# Laminar Tube Floc Team - Fall 2013

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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[3]hypothesis, flocs that reach a ceratin 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 are not able to settle out from the suspension. The purpose of this series of experiments was to test this hypothesis and, if valid, to determine the most effective way to break up flocs in order to have the highest removal rate of colloidal particles. A base case was devised to serve as a control showing residual turbidity with varying coagulant doses. Clamps of varying size were used in subsequent experiments to break flocs, and the results were compared with the base case. Because variation in results had been a previous issue, experiments were replicated to ensure the extent of their variability was understood and quantified. Results from the base case showed that higher levels of coagulant dosage decrease the residual turbidity of the water. The data collected from clamp size experiments suggested that breaking up flocs once in the middle of the tubing arrangement can either improve or worsen the flocculator performance depending on the clamp size used. Use of a 4mm clamp to break up flocs resulted in a higher residual turbidity than the base case while a 5mm clamp resulted in a lower residual turbidity than the base case. Only the 4mm clamp however, had results that were significantly different than the base case. The results found from this semester's experiments suggest further testing of clamp size on flocculator performance.

## 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 was to further the understanding of the flocculation mechanisms by extending the work of previous groups and to test Swetland et al.'s[3] hypothesis that large flocs are not effective in removing colloids. Preliminary results from prior research performed in previous semesters indicate that having constrictions on the tube flocculator to create zones of high energy dissipation can be effective in breaking up flocs. Using these results as an initial start, the experiments performed this fall semester consisted of a base case and experiments that tested different sizes of flow constrictions. The base case dictated the optimal coagulant dosage that was used in the variable experiments, and was a control set of results used for comparison and data analysis.

The goal of the Laminar Tube Floc team this semester was to prove whether using clamps to constrict the flow assists in lowering the residual turbidity of the water leaving the plant, and if so, to use the results to create a more efficient design for the flocculator in the water treatment plant. Although past groups' work have shown that clamps are useful in breaking up flocs and lowering residual turbidity, we performed a set of experiments that have replicable results, providing enough 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 [1, 7]. In laminar flow, energy dissipation rate and the velocity gradient can be related as follows [5]:

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

where G = velocity gradient, $\varepsilon$ = energy dissipation rate, and $\nu$ = 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 [3]. Due to the presence of laminar flow in our experimental flocculator system, the parameter G is valid for the model [1]. 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 [7].

Swetland et al. (2012) [3], 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 [3]:

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

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. $\log(G\vartheta\Gamma\Phi^{\frac{2}{3}})$), $\vartheta$ = hydraulic residence time, Γ = fractional coverage of colloids by coagulant, and Φ = floc volume ratio.

equation (2) 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 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. [3] experimented with a range of influent turbidities from 5 NTU to 500 NTU and found that 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 number of particle collisions per unit time in a laminar flow flocculator is proportional to G and the time available for collision is $\vartheta$. 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 $\vartheta$) to flocculate. However, in Ian Tse's studies [5], 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 [5]. The point past G$\vartheta$ values of 15,000 was where the flocs reached a condition in which they were at a size limited by breakup. High fluid shear levels would hinder the flocs from growing in size at high G values. From the results of Ian Tse's study [5], 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 400 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 was used to maintain the synthetic raw water (SRW) influent turbidity at 100 NTU.

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

## 2 Flocculator Setup

The laminar tube flocculator consists of three coiled 3/8" tube arrangements connected in series. The total tubing length used was 83 m; one 23 m long silicone tubing arrangement was 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. The cardboard tubes are used for structural support.

Silicone tubing was chosen to be the middle segment used for experimentation due to its elasticity, allowing the tubing to quickly reform to its original shape after clamps are removed. The research group from the summer discovered that "dents" were left on 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 and possibly break up when entering regions where dents were left. To prevent such 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 only 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 measured 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 into 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 travelling into the pressure sensor tubing.

To gain more accurate results for our experiments, we are using the flocculation residual turbidity analyzer (FReTA) experimental device to provide accurate measurements of the residual turbidity of the water leaving the flocculator [5]. FReTA is a measurement apparatus that is capable of measuring floc sedimentation velocity without physically affecting the flocs that are formed within the flocculator.

FReTA is composed of three main parts: an inline turbidimeter, a transparent glass column, and an electrically actuated ball valve. Each component of this setup contributes to providing the residual turbidity over a certain period of time.

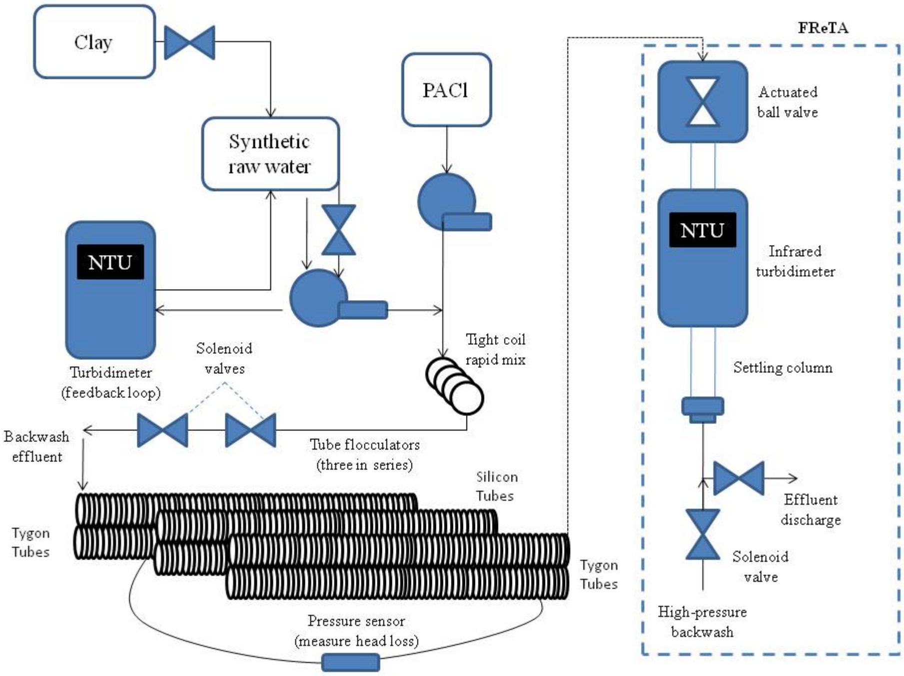

Figure 1: Schematic of complete experimental assembly (Update from Ian Tse's master thesis, Aug. 2009)

## 3 Base Case

Our initial experiment was a base case with no clamps. The purpose of this base case was to serve as a control to compare with results from the experiments with flow constrictions. Two different trials were performed using a linear PACl dosage of 0 mg/L to 10 mg/L in increments of 1 mg/L.

One trial was performed with PACl dosages incremented according to the power law:

$$Dosage = coefficient * base^{maxreps}$$

where coefficient = .25 mg/L, base = 1.25 mg/L, and maxreps = 10.

The power law dictates more dosages in the 0-2 mg/L range due to its exponential factor. The power law allowed us to gather more data points in the lower dosage range, giving a closer look into which dosage causes the residual turbidity to start to drop significantly.

## 4 Clamp Size Experiments

To test the floc break-up theory, different clamp sizes were used to see how the sizing of the clamp on the flocculator tubing affects the residual turbidity. This experiment consisted of placing one clamp in the middle of the middle tubing arrangement. Nine total runs were performed per trial: three with 0 mg/L of PACl, three with .8 mg/L, and three with 1.8 mg/L. This procedure was done using no clamps, a 4 mm clamp, and a 5 mm clamp. The 4 and 5 mm clamp tests were both repeated twice, and the base case test was repeated three times. Multiple tests were conducted to gain more data on the effect floc breakup had on lowering the residual turbidity of the water. Clamp sizes of 4 and 5 mm were chosen to be tested because the results from this past summer's end clamp testing showed that only the 4 and 5 mm clamps out of the clamp sizes of 4, 5, 5.5, 6, 6.5, and 7 mm showed significant floc breakup. Trials were run using no clamp to use as a base case for comparison. A dosage range of 0-2 mg/L of PACl was chosen from the results of the preliminary base case. The results of the base case suggested that a dosage range of 0-2 mg/L would be good for testing because in that range, residual turbidity drops significantly, but also achieves close to the asymptotic residual turbidity value of around 1.5 NTU.

## Part IV

# Results and Discussion

## Base Case

Two trials for the base case were run with the setup described above using the linear PACl dosage, and one trial was run using the power law PACl dosage. No clamps were used for these three experiments.The resulting data are shown in figure2. An increase in coagulant dosage tends to result in a lower residual turbidity. The mean residual turbidity for runs with no coagulant were in the range of 68-74 NTU and were omitted from the graphs so that the graphs could provide a closer look at the turbidities of runs that used coagulant. Values of 68-74 NTU for the effluent residual turbidity are strange for runs using no coagulant, because theoretically, the effluent turbidity should equal the influent turbidity when no coagulant is present. The water entering the flocculators had a turbidity of 100 NTU, however without adding any coagulant, the residual turbidity dropped down to around 70 NTU.

We infer the cause of the decrease in effluent turbidity in the absence of coagulant to be that backwash was not sufficient enough in removing the coagulant stuck to the walls of the flocculator. After each experiment, the tubes would be cloudy due to the residual coagulant and flocs adhered to the tubing of the flocculator. To prevent the 30% drop of turbidity from the original inlet turbidity during runs with 0 mg/L of PACl, all subsequent experiments were preceded with a backwash using a sponge to scour residual coagulant and leftover flocs stuck to the walls of the tubes. Additional actions to correct this problem included cleaning the turbidimeter sample cells, the glass column within the FReTA setup, and checking the influent and effluent turbidimeter readings against each other. Another possible solution would be to set a higher flow rate through the flocculator. Having a higher flow rate would cause floc particles that attach to the tubes to be scoured off, but would also increase the energy dissipation rate, causing possible break up during flocculation.

One of the theories regarding why the residual turbidities measured during the experiments fluctuated was that an insufficient ramp down time caused there to be an upflow within FReTA that led to slightly altered turbidity readings. We tested this hypothesis by using a PACl dosage of 10 mg/L and switching between the end of Ramp-down state and the beginning of Close Ball Valve state. A concentration of 10 mg/L PACl dose was chosen so that large flocs would be flowing through the tubes, allowing for higher visibility. The purpose of this test was to observe if flocs moved upwards between the process of switching states. The test results showed that the flocs did move upwards, indicating that the water flow within FReTA had not slowed down enough at the end of the ramp-down state as the result of an insufficient ramp down time. The upward motion of flocs would cause an incorrect reading within FReTA for residual turbidity. To prevent an insufficient ramp down time from disrupting our data, we increased the ramp down time from 14 seconds to 31 seconds.

The base case data resulted in a downward trend for residual turbidity with fluctuations as the PACl dose increased. These oscillations may have been caused by the fluid upflow in FReTA, as discussed above. The residual turbidity starts to level out around a dosage of 2 mg/L to 1 NTU with fluctuations of +/- .5 NTU.From these three trials of the base case, we decided to test a PACl dosage range of 0-2 mg/L because in this range, the residual turbidity dropped significantly and reached a residual turbidity of around 1 NTU +/- .5 NTU.

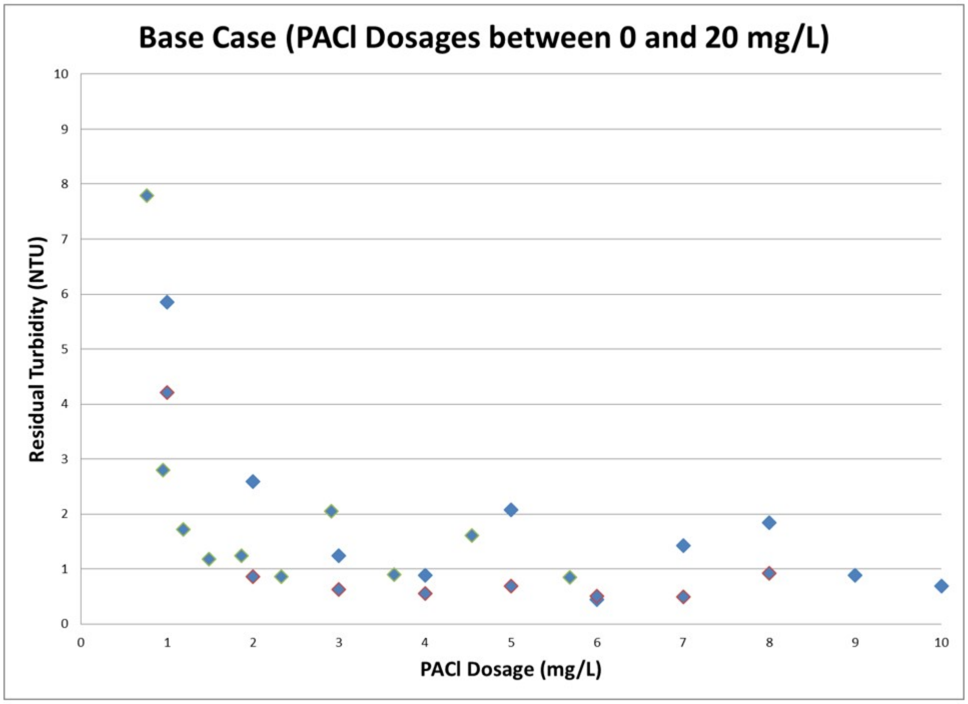

Figure 2: Base case raw data from two trials using linear dosing and one trial using power law dosing

An experiment with eight runs was performed with no coagulant added and still yielded results with fluctuations where the points alternated between being higher and lower than the previous run (figure3). These results suggest that the fluctuations are not a result of differing coagulant doses, but rather a systematic turbidimeter issue.

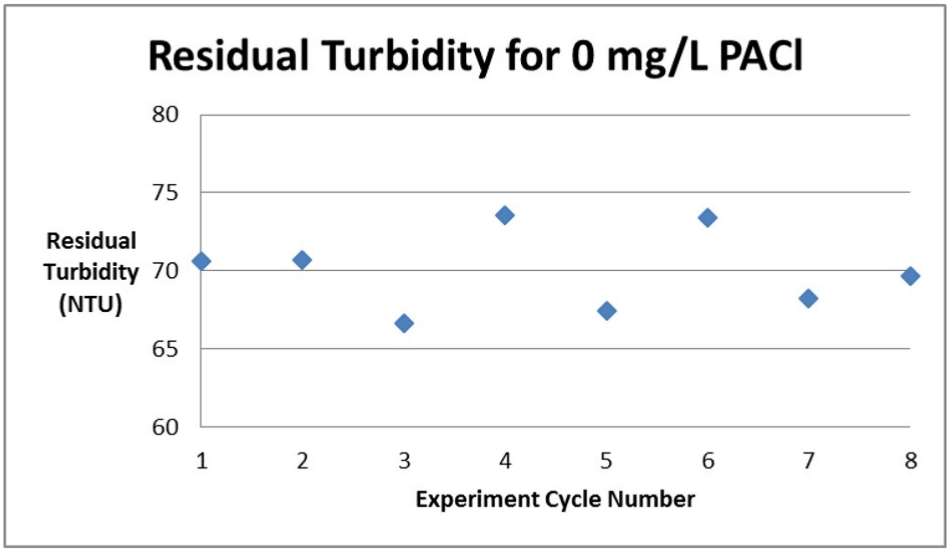

Figure 3: Alternating fluctuations in a zero dose trial

## Clamp Size Testing

The second half of our research involved testing the floc breakup theory through the use of clamps. A set of runs was conducted to create a new base case to compare to clamp testing data. The base case for dosages of 0, .8, and 1.8 mg/L are shown in figure 4. Nine total runs were performed for each dosage to form the base case, with low standard deviations of less than .6 NTU. The results for 0 mg/L dosage were omitted from the graph because the residual turbidities using no coagulant do not actually help draw any conclusions about the effectiveness of floc breakup. Omitting the data points for 0 mg/L dosage also allows a closer look at the results for .8 and 1.8 mg/L of PACl.

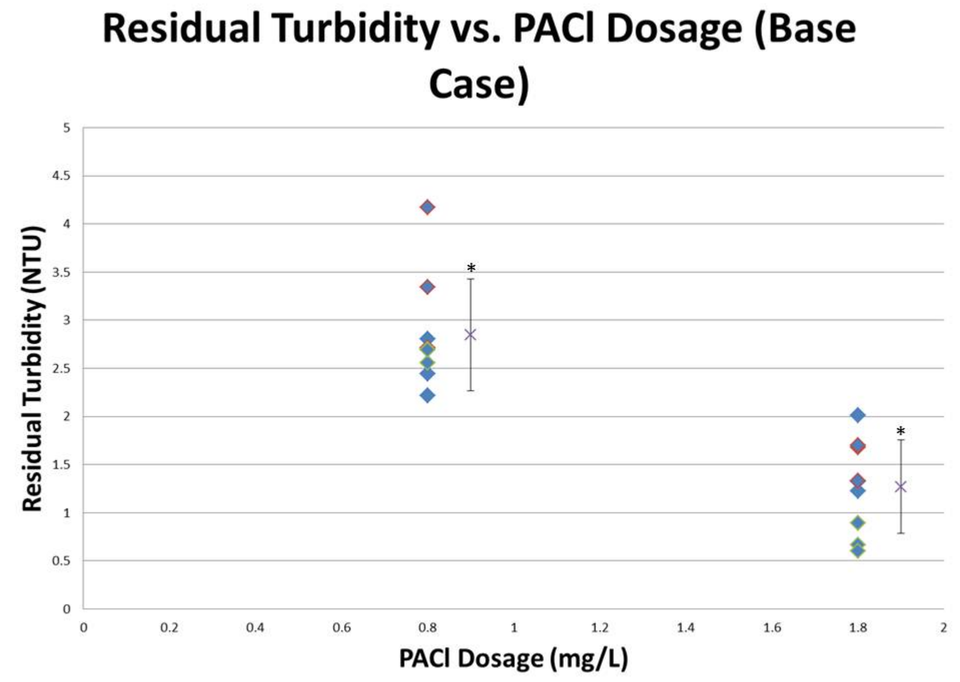

Figure 4: Base case data with the mean residual turbidity depicted by the ’x’ marker with error bars (*the mean residual turbidity is still for PACl dosages of .8 and 1.8 mg/L and are offset on the graph as to not overlay the raw data)

The 4 mm and 5 mm clamp testing also produced data with low standard deviations below .7 NTU, as shown in figures 5 and 6, respectively.

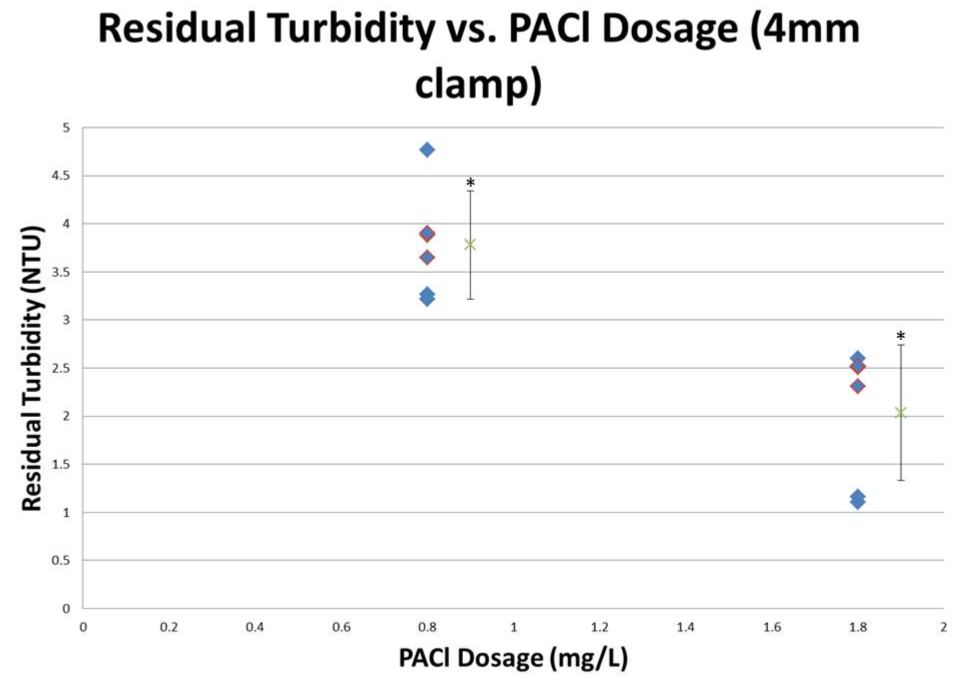

Figure 5: 4 mm clamp testing data with the mean residual turbidity with error bars

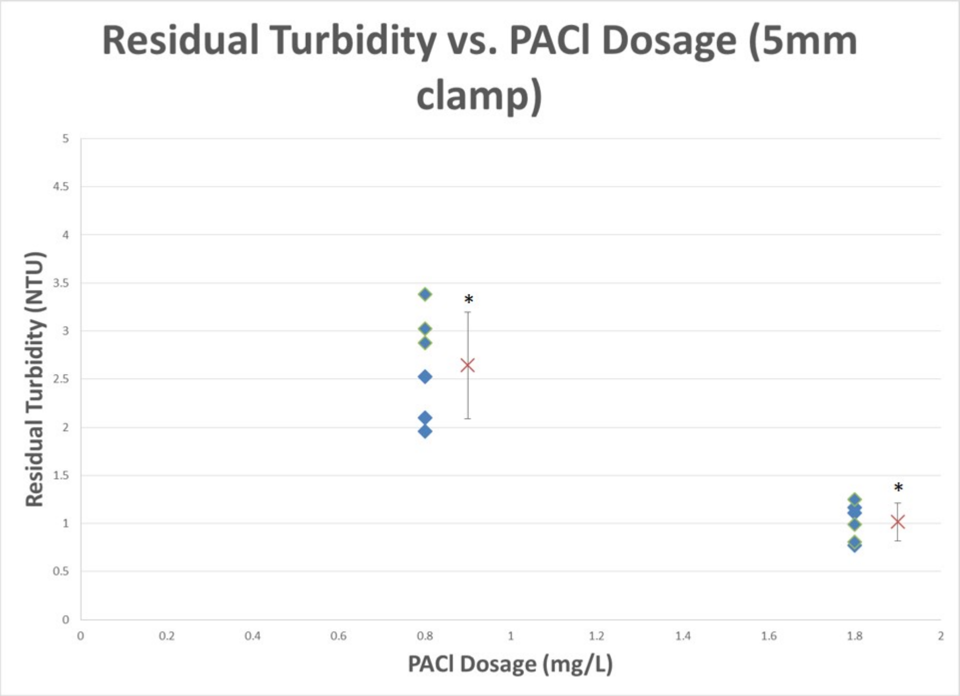

Figure 6: 5 mm clamp testing data with the mean residual turbidity with error bars

The results of our clamp testing show that the mean residual turbidity for 4mm clamp was higher than that of the base case at both dosages, while the 5mm clamp produced lower mean residual turbidities than the base case at both dosages. The error bars overlap, however, as shown in figure 7, so these differences may not be significant and do not justify concluding that use of a 4mm clamp to break up flocs yields poorer results than no clamps and that using a 5mm clamp to break up flocs yields better results than no clamps. For further analysis, a two sample t-test, was conducted to compare the mean residual turbidities between the base case and 4mm clamp, and the base case and 5mm clamp at PACl dosages of .8 and 1.8 mg/L. The differences in mean residual turbidities for the base case and 4mm clamp were significant for both dosages. P-values of .0081 and .036 were calculated for .8 and 1.8 mg/L, respectively. The differences in mean residual turbidities was found to not be significant for both dosages between the base case and 5mm clamp. The respective p-values were .934 and .177. These statistical results suggest that using a 5mm clamp to break up flocs in the middle of the tubing arrangement does not significantly improve flocculator performance, but instead using a 4mm clamp significantly decreases flocculator performance.

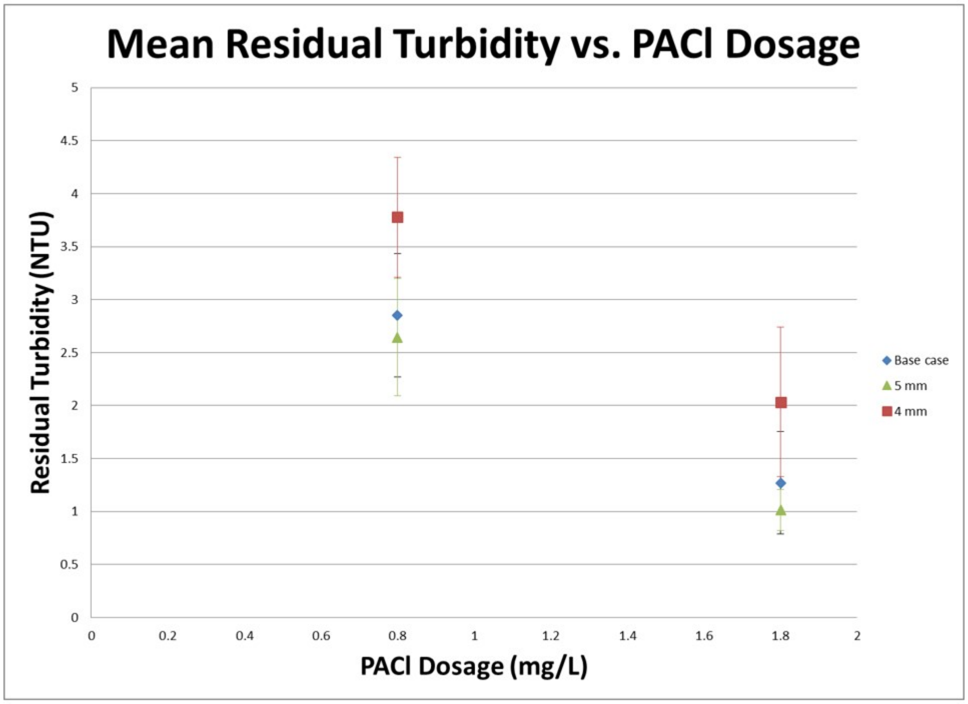

Figure 7: Mean residual turbidities with error bars for base case, 4mm, and 5mm clamp

The data collected from 4mm clamp testing suggest that the floc breakup theory is incorrect; breaking up flocs to allow them to reform does not lower the overall residual turbidity. One possible explanation for this result could be that the fluctuations in our residual turbidity values were too great to allow us to detect differences in NTU levels that the floc breakup caused. The 5mm clamp testing shows that the floc breakup theory is plausible by producing lower residual turbidities than the base case. The results for 5mm clamp testing, however, were found to not be significant. These two differing results from the 4mm and 5mm clamp testing raise an interesting possible explanation that the size of broken up flocs affect their ability to grow larger. The energy dissipation rates calculated for the 4mm and 5mm clamp were 7838 mW/kg and 387.7 mW/kg, respectively. Based off our results, an energy dissipation of 7838 mW/kg is too high.

Experiments conducted by State Key Laboratory of Urban Water Resource and Environment demonstrate that efficient flocculation can be significantly improved through floc breakup and regrowth of flocs under appropriate conditions. The units used in their results were 10^-3 mol/L of Aluminum per mole of PACl and a range of 0 to 9 NTU for residual turbidity. Having higher PACl concentrations of 0.2 and 0.4 10^-3 mol/L resulted in the turbidity levels being higher after floc breakage than before floc breakage. Using 0.04 and 0.08 10^-3 mol/L for PACl concentration resulted in the turbidity being lower after floc breakage than it was before floc breakage. These results suggest that there is a range of coagulant doses that leads to appropriate conditions where flocculation is improved with floc breakup [8].

Because the size and structure of flocs, added coagulant, and applied shear force all affect the efficiency of floc breakup, it is possible that the PACl concentration used for clamp testing was too low to create large enough flocs for effective floc seperation. Using a higher PACl concentration might have resulted in larger flocs flowing through the system. However, 0 to 2 mg/L PACl concentration was chosen based on the assumption that, since this range of coagulant dosage was effective enough in decreasing the residual turbidity from 80 NTU to around 5 NTU, there must be sufficiently large sized flocs being formed.

Pressure head data was also collected alongside the experiments (shown in figure 8, figure 9, and figure 10). The pressure head was highest for the 4mm clamp, followed by the 5mm and base case. The difference in pressure head for 5mm and base case are much smaller than the difference in pressure head between 4mm and base case, which is expected because the 4mm clamp is smaller and would therefore pinch the tubing more.

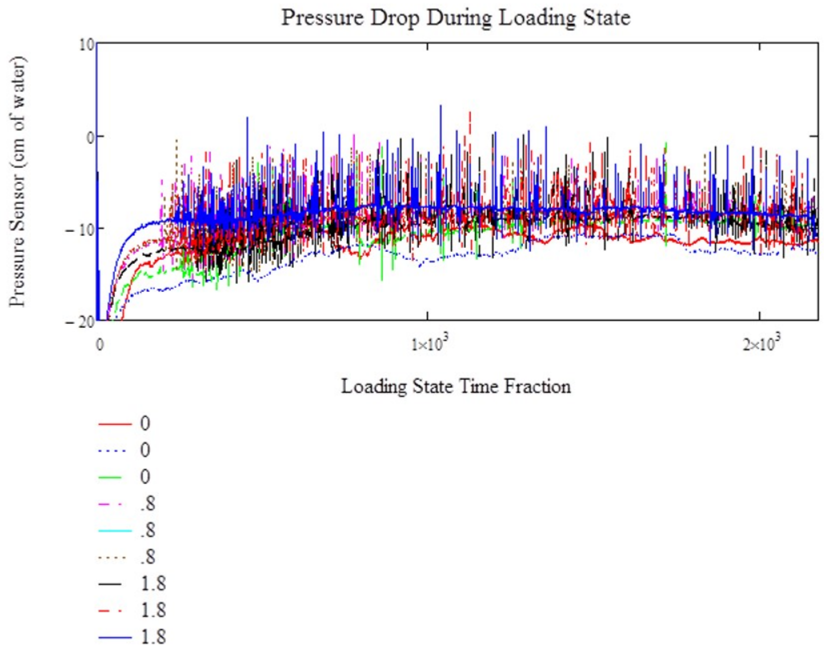

Figure 8: Pressure head for base case (units for the legend is mg PACl/L)

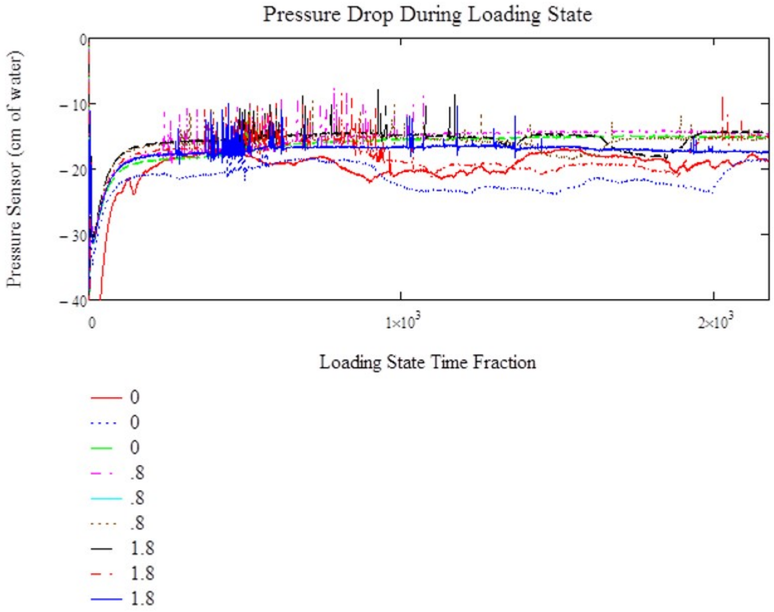

Figure 9: Pressure head for 4mm clamp (units for the legend is mg PACl/L)

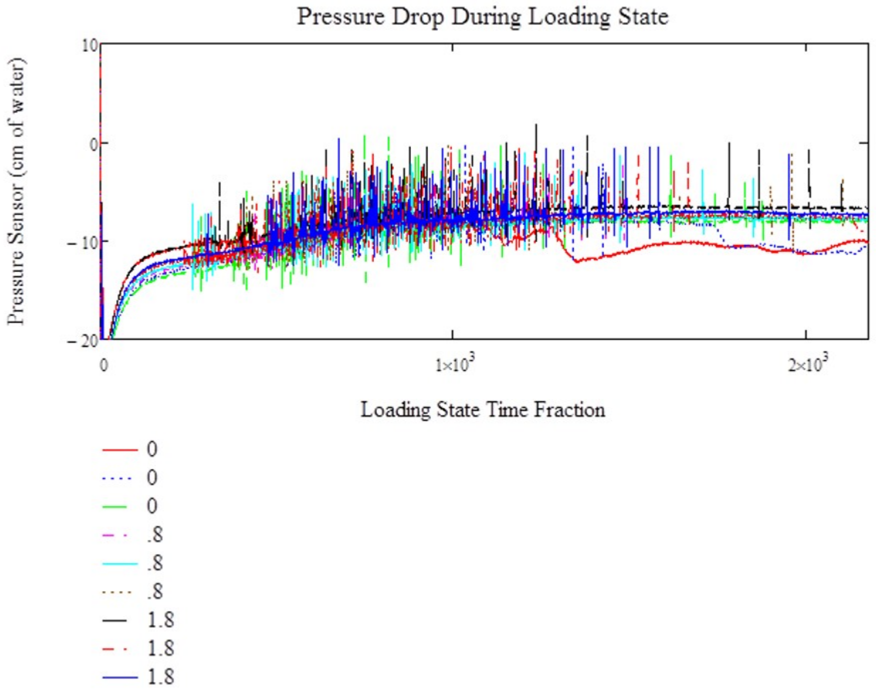

Figure 10: Pressure head for 5mm clamp (units for the legend is mg PACl/L)

# Part V

# Conclusions

From the three trials done on the base case, it is evident that the addition of coagulant is effective in decreasing the residual turbidity significantly within the range of 0 to 2 mg/L. At greater doses there is still a continuous downward trend however the change in residual turbidity is not as dramatic as it was within the range of 0 to 2 mg/L. A dosage range of 0 to 2 mg/L also avoids the fluctuations that occur at higher dosages. Conclusions that can be drawn from the three base case trials of the first half of our research are that a coagulant dosage range of 0 to 2 mg/L causes a significant drop in residual turbidity. Initial concerns were that the flocs sizes created from this lower dosage range would not be effective for clamp testing. However, due to lower dosages' ability in significantly lowering the residual turbidity, the conditions selected for our research involved experimenting with clamp sizes with a PACl dosage range of 0 to 2 mg/L.

The tests on clamp sizes did not produce significant differences relative to the base case and do not prove floc break-up is or is not effective in reducing the residual turbidity. The t-test showed that 4 mm clamp significantly increased the residual turbidity, demonstrating that in this case, breaking up flocs was not effective in decreasing residual turbidity. For the 5 mm clamp test, the t-test showed that the results were not significant enough to have a clear correlation between floc break up and resulting turbidity levels. No clear conclusions from our experiments can be made in regard to the floc breakup theory. One of the clamp sizes refuted the floc breakup theory while the other was not significant enough to prove or disprove the theory. The work done from this semester can guide future semesters in further testing of the floc breakup theory.

# Part VI

# Future Work

The results obtained from 4mm and 5mm clamp testing are not conclusive in proving or disproving the floc break-up theory, so additional experiments should be performed. While the summer research suggested that clamp sizes above 5mm are not effective in showing significant floc break-up, perhaps breaking up flocs to a lesser degree using larger clamp sizes could be beneficial in allowing flocs to regrow and collect more colloids.

Experiments conducted by Colorado State Univerisity on cyclic shearing recovery [2] show that as more shear cycles occur with time, recovery of floc aggregates caused by shearing forces becomes impaired as evidenced by a decrease in recovery slopes. These experiments suggest that experiments with multiple clamps on the flocculation system are unlikely to improve particle removal. Although literature by McCurdy has indicated that multiple breakups of flocs results in poor recovery, testing could still be performed on the tube flocculator regarding clamp number. A range of 1-16 clamps spaced evenly across the tube flocculator can be tested to see how multiple clamps affects the residual turbidity. A tapered flocculator could also be tested, where the energy dissipation rate is decreased with each subsequent tube arrangement. By lowering the energy dissipation rate as the flocs travel, the flocs would experience less shear, possibly allowing them to collect more particles.

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