Tube Floc Literature Review

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Abstract

Over the Summer of 2013, the Tube Flocculator team's overall goal was to further the understanding of floc breakup in order to heighten flocculator performance. Specifically, this was done by examining a single clamp's effect on flocculation, as well as finding the optimal orifice size while using multiple clamps. The effects of the clamps were predicted to increase overall colloid aggregration which would prove beneficial for the next step in AguaClara's process: sedimentation. Based on the results found over this summer, some conclusions can be made. One conclusion based on the end-clamp experiments is that larger orifice sizes display lower mean residual turbidities. Another is that, for a 28-meter-long flocculator, an evenly-spaced sixteen-clamp configuration appears to be better than using no clamps, depending on the clamp size used. The the eight-clamp configuration appears to not be any more effective than a no-clamp control, while a four-clamp configuration appears to show improved flocculator performance for certain clamp sizes. In future work, these findings can be applied to the full scale floculator in hopes that floc breakup will prove useful for plant performance.

Part I
Introduction

As a continuation of work previously conducted on the tube flocculator, the team of Summer 2013 was tasked with improving the performance of the tube flocculator by initiating floc breakup during flocculation. Prior work has suggested that it is not advantageous to allow flocs to continuously grow to their maximum size, as flocs that have reached their maximum size do not effectively contribute to colloid removal.[3] Previous experiments studying floc breakup have only begun to explore the possible clamp configurations for floc breakup. A two-clamp configuration was tested with three different clamp sizes, as well as a four-clamp and eight-clamp configuration with one clamp size. All of these were done with a 10 mg/L PACl solution.[2] In order to continue this investigation, this summer's experiments tested more concentrations, clamp sizes, and clamp configurations with the intent of gaining a better understanding of the effect of floc breakup on flocculator performance.

The first set of experiments studied the effect of placing a constriction at the end of the tube flocculator. This allowed the effect of the constriction to be isolated and measured by FReTA. The aim of this line of experimentation was to gain a fundamental understanding of the effects of tube constriction on floc breakup. In future work involving more complicated constriction configurations, this will provide a foundational basis for understanding the effects of a single constriction on floc breakup.

The next set of experiments examined the optimal orifice size for floc breakup by using multiple clamps of the same size. Clamps of each size were placed on the tube flocculator in groups of four, eight, and sixteen, and their effect on effluent turbidity was observed. The ideal orifice size will result in lower residual turbidities and higher pC* values than a control (i.e. no clamps). This will prepare the way for the next set of studies examining the optimal placement of clamps for floc breakup.

Part II

Literature Review

Flocculation is a stage during water treatment in which gentle mixing is used to bring suspended precipitates in contact so that they can adhere to one another and settle. In terms of the efficiency of water treatment in removing particles, flocculation is the most important process. The mechanisms commonly used to accomplish this in American water treatment are axial-flow impellers, paddle flocculators, and baffled chambers. AguaClara uses baffled chambers. In designing a flocculator for water treatment, the two important empirical parameters are the velocity gradient (G) and the hydraulic residence time (ϑ). When selecting a value for G, it is important to select a value high enough to achieve thorough mixing and prevent premature settling, while also selecting a value low enough to avoid shearing the flocs apart and dispersing them.[1] In laminar flow, velocity gradient (G) is proportional to energy dissipation rate (ε) and kinematic viscosity (υ).[3]

$G = \sqrt{\frac{\varepsilon}{\upsilon}}$

G=velocity gradient: the difference in velocity between adjacent layers of fluids [s^{-1}]

ε=energy dissipation rate, a measure of mixing intensity [$\frac{m^2}{s^3}$]

υ=kinematic viscosity of water [$\frac{m^2}{s}$]

Hydraulic residence time (ϑ), or retention time, is a property of the reactor that describes the average time a particle stays within the flocculator [s].

Swetland et al. 2012 described a predictive laminar flocculation model which is governed by the following equation[3]:

$$C* = \frac{1}{\beta G \theta \Gamma \phi^{\frac{2}{3}}} \tag{1}$$

where:
G =mean velocity gradient
ϑ =hydraulic residence time
Γ =fractional coverage of colloids by coagulant
ϕ =floc volume fraction
$C*$ =residual settled water turbidity divided by influent turbidity
$\beta = \frac{\eta_{PACl}}{V_{capture}}$, where η is a fitted parameter, and $V_{capture}$ is capture velocity

$$pC* = -\log(C*) = \log\left(\beta G \theta \Gamma \phi^{\frac{2}{3}}\right)$$

From 1, it can be seen that as average energy dissipation rate (directly related to average velocity gradient) increases, the effluent turbidity decreases, signifying a higher turbidity removal. However, when average energy dissipation rate gets too high, the flocs start to break up, resulting in particles that cannot be captured by the sedimentation tank because of their slower settling velocity. Thus, the flocculator should be designed to maintain the energy dissipation required to limit the floc size that corresponds to the required capture velocity.

The choice to limit floc size is in opposition with the popular hypothesis about particle attachment: “colloids can attach to all flocs.”[4] From past experiments, it was found that when flocs grow too large, they reach a point at which no more growth can occur.[2]When the flocs reach a certain size, the fluid shear around the floc becomes too great for any smaller particles to pass through, and the particles cannot attach to the floc. This leads to Dr. Weber-Shirk’s hypothesis, “large flocs are useless” and also ties in the need to limit the larger floc sizes so that the overall number of particles agglomerated in flocs can increase. [4]

In order to apply these conclusions to the tube flocculator used by AguaClara, it is necessary to determine the energy dissipation rate expected for changes made to the geometry of the tube flocculator. From the work done in Spring 2013, it was theoretically derived that the relationship between energy dissipation rate and orifice size (of a constricted tube) is described by:[2]

$$\epsilon_{breakup} = \frac{64 * \Pi_{jet}^3 * Q_{plant}^3}{H_{tube}^2 * (8ID^3 - H_{tube}^3 - 12H_{tube}ID^2 + 6H_{tube}^2 ID)} \tag{2}$$

Plotting this equation with respect to clamp size (shown in figure 1) we see greater changes in energy dissipation rates with clamp sizes ranging from 4mm-7mm.

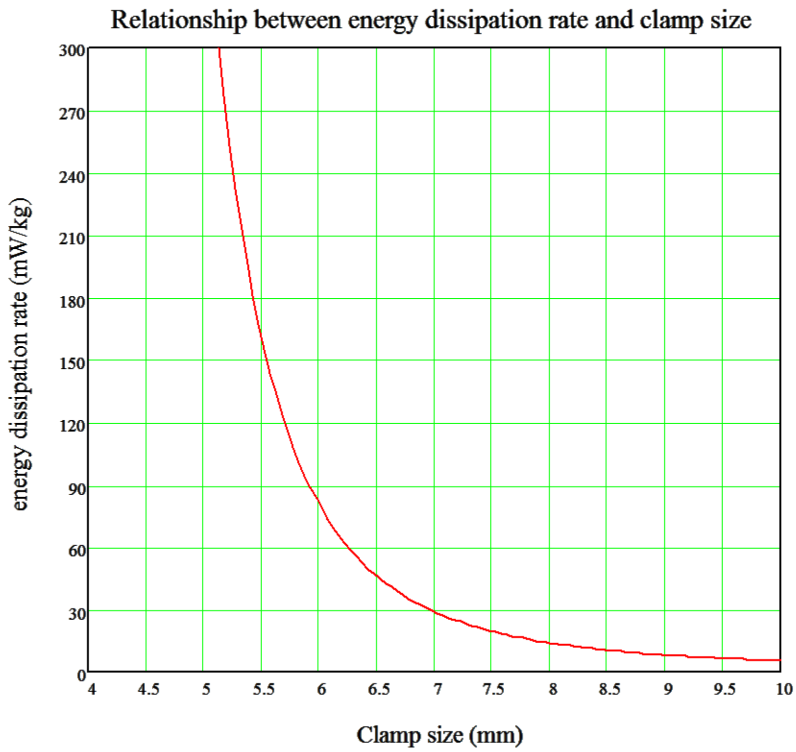

Figure 1: Energy Dissipation Rate vs. Clamp Size [2]

Previous experiments with clamps on a tube flocculator comprised of silicone tubing have shown greater energy dissipation at breakup points with smaller clamp sizes, and lower residual turbidity with more clamps.[2] The silicone tubing that was used in Spring 2013 was tested as a potential method to stop the adhesion of coagulant to the inner walls of the tube flocculator. Results showed minor improvements in this regard. However, the silicone tubing is less economical than Tygon tubing. Experiments since this time have been conducted using the Tygon tubing.

Past experiments to compare the effects of having or not having clamps on the tube flocculator remained inconclusive due to the low residence time and the low coagulant dose.[2] In future experiments, a higher range of coagulant doses will be used, which will cause the maximum size of the flocs to vary. The final report for Spring 2013 also recommended that future experiments explore the effect of multiple clamps on the system by varying their size, number, and configuration. Also recommended was an examination of the effect of using a tapered tube for the flocculator. The underlying principle is that, as the tube diameter increases, the energy dissipation rate decreases. This creates regions with different levels of floc breakup, with higher floc breakup at the beginning and lower floc breakup at the end. Potentially, this will allow flocs to reach a higher maximum diameter.

Part III
Methods

1 PACl and Clay Preparation

PACl was prepared at 400 mg/L in aqueous solution. For experiments conducted using the Honduran PACl, the solution was prepared using stock in powder form and tap water. For experiments conducted using the American PACl, a 30 g/L stock solution from Cornell's water treatment facility was diluted to 400 mg/L using deionized water. A stock clay solution of 10 g/L was fed to the synthetic raw water (SRW) tank at a controlled rate to maintain SRW turbidity at 100 NTU. The stock clay solution was prepared by mixing 10 g of clay with 1 L of tap water.

2 End Clamp Experiments

Experiments were conducted using the FReTA apparatus and a tube flocculator made up of 28 meters of Tygon tubing. Tygon tubing was used because it is more economical than silicone tubing. Previous experiments suggest that there is little difference in tube floc performance between systems with Tygon tubing and silicone tubing.[2] In order to achieve constriction at the end of the tube floc apparatus, clamps ranging in size from 4 mm to 7 mm were applied to the section of tubing directly above FReTA. Hoffman clamps were used for clamp sizes where fixed-width aluminum clamps were unavailable.

3 Multi-Clamp Orifice Size Optimization

The next type of experiment was conducted using American PACl and the same tube flocculator apparatus. As these experiments required a total of 96 clamps to be made, a different manufacturing process was needed to get the necessary clamps in a more timely and economical way than machining them out of 1/8" aluminum stock. The team decided to use 1/8" plexiglass, and cut clamps out of it. The team prepared an AutoCAD file with templates of the clamps that were slightly larger than their aluminum counterparts in order to give them more resistance to flexure. The clamps were then cut by a laser cutter in the Architecture, Art, and Planning Department. The first set of experiments with these clamps used four clamps, with a clamp placed at every seventh coil. The second set used eight clamps, with one clamp every fourth coil. The third set used a sixteen-clamp configuration, with one clamp placed at every two coils along the tube flocculator. All clamps were placed on the underside of the tube flocculator. Coagulant dosage was linearly increased from 0 to 8 mg/L.

Part IV
Results & Discussion

4 End Clamp Testing and Comparison of Honduran and American PACl

The first set of experiments conducted in the summer of 2013 examined the effect of increasing the energy dissipation rate at the end of the flocculator by using a single clamp. The constriction was expected to cause flocs to break up, and the intent was to measure the extent of floc breakup achieved by different energy dissipation rates. In the first trials of these experiments, the available coagulant was orange powdered PACl from Honduras.

For each of these trials, the residual turbidity remained fairly close to the influent turbidity (~100 NTU). The expectation had been that the residual turbidity would increase with decreasing clamp size, as shown in 1. The results generally followed this trend, but the no-clamp case deviated from this trend, as it would have been expected to have a higher pC* than all of the clamped trials. The data can be seen graphed in 2.

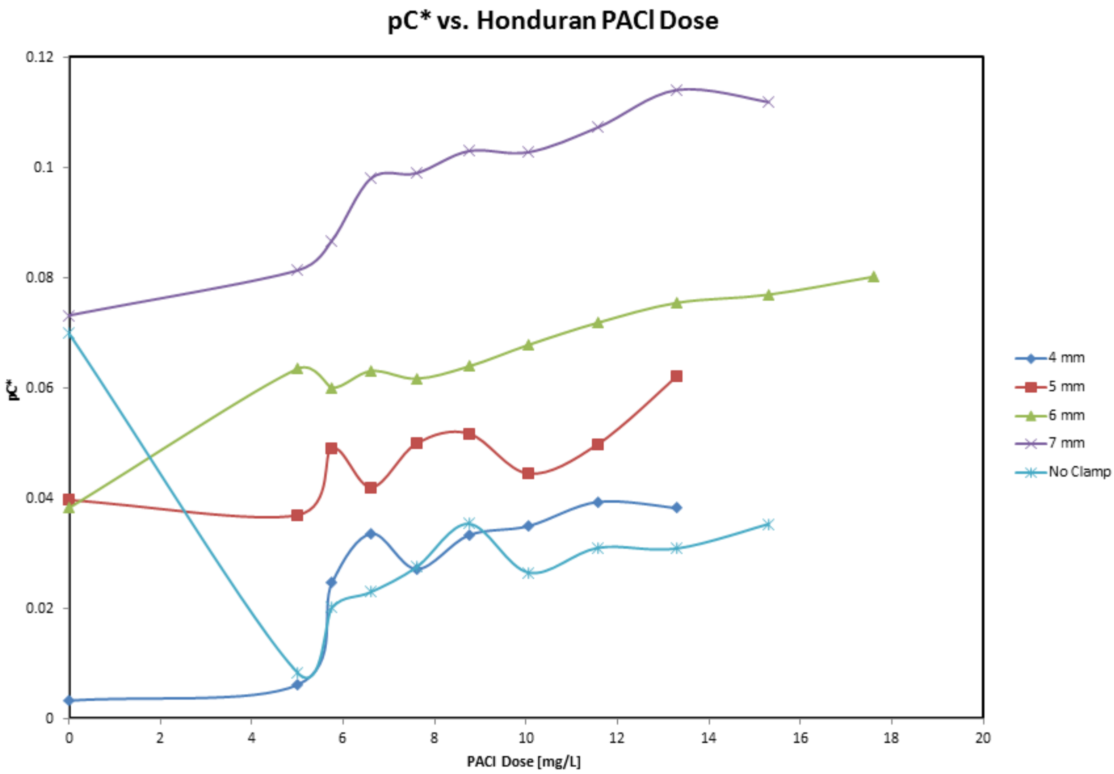

Figure 2: pC* for End Clamp Experiments Performed with Honduran PACl

The results of the experiments using Honduran PACl are questionable, as the PACl would often precipitate out of solution (settling near the outlet of the PACl stock tank) before fully dosing the system. This could have caused inconsistencies in the dosages of PACl between the different trials as well as inconsistencies within a single trial.

Experiments conducted with the American PACl also followed the expected trend, but showed a much greater drop in residual turbidity. At clamp sizes higher than 5 mm and PACl doses above 8 mg/L, varying the clamp size seemed to have little effect on the residual turbidity. An unexpected result of these experiments is that the majority of the clamp sizes yield higher values of pC* than the unclamped control for most of the PACl concentrations. These results are shown in 3.

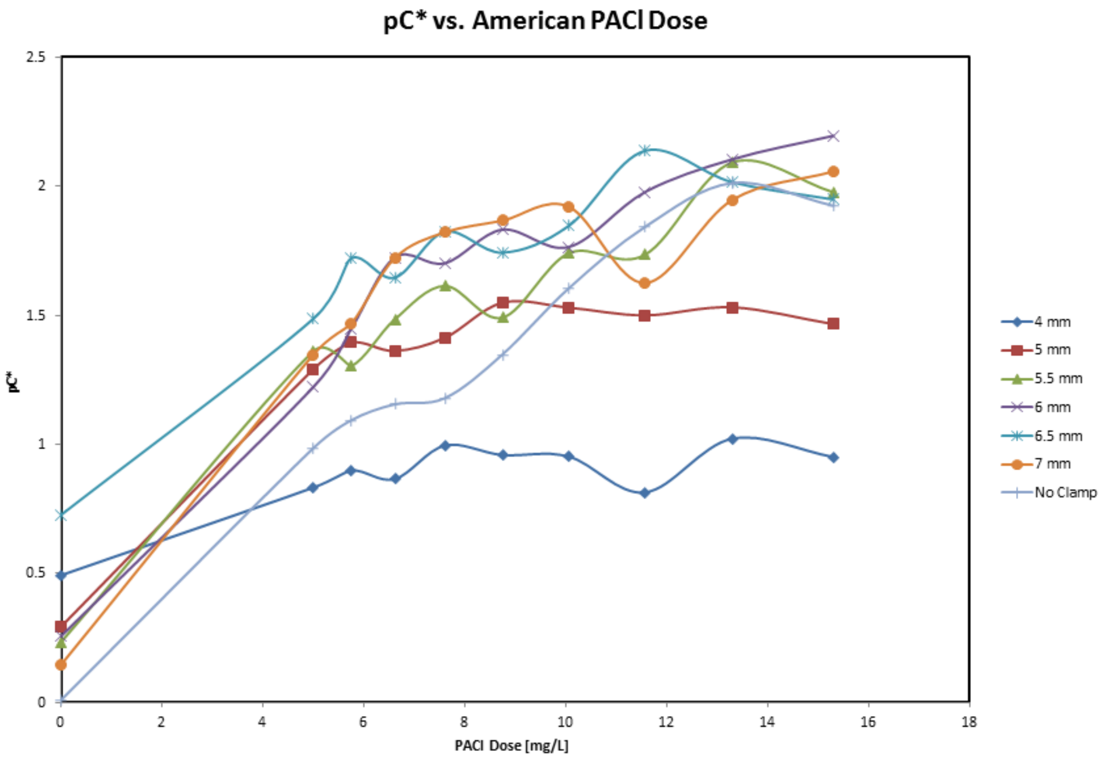

Figure 3: pC* for End Clamp Experiments Performed with American PACl

The results of the end clamp testing experiments with respect to the different PACl sources indicate one of three possibilities. The first is that the Honduran PACl may have become inactive, or previously coagulated, due to exposure to moisture in storage. This seems likely due to the clumpy consistency of the powdered PACl. The next possibility is that the concentration of the stock powdered PACl was incorrectly assumed to be 100 percent. This would have caused the 400 mg/L PACl solution to contain less than 400 mg/L of PACl, which would explain the low coagulant activity in the first trials. In Honduras, a mass of powdered stock is weighed and added to the mixing tank for the given volume. The issue is translating the same dosage using a liquid stock with a differently documented PACl concentration. The last possibility is that the chemical purity of the American PACl is significantly higher than that of the PACl.

For future work, it is recommended that the end-clamp experiments be repeated at a lower dosage range. The range between 0 to 5 mg/L of PACl has not yet been studied, and may give some other insights into the effect of clamps on flocculation. These experiments should be performed with American PACl. Whether this dosage range or a lower dosage range is decided to be more useful in understanding the effect of constriction, many more trials should be conducted. As the data fluctuated substantially, having more values would help to better understand these effects by averaging out the fluctuations.

5 Multi-Clamp Orifice Optimization

In these experiments, the coagulant dosage has been reduced from 5-15 mg/L to 0-8 mg/L for two reasons: the American PACl was significantly more effective than the Honduran PACl and the range from 0 to 5 mg/L was neglected during the end clamp experiments. Reducing the PACl dosage accentuates the difference in clamp performance, as the residual turbidity curves rapidly approach an asymptote of around 5 NTU after a PACl dose of around 8 mg/L.

A new parameter was studied to gain a better picture of the actual floc size. Settling velocity is directly related to particle diameter, so by studying the particle velocity, it is possible to get a sense of the particle diameter associated with each clamp size and concentration. To obtain settling velocity, it is assumed that at 50 NTU (the halfway point between the synthetic raw water and pure water), half of the particles have settled below FReTA, and half still remaine above FReTA. This halfway point represents the average particle size. To obtain this number from the raw data, a function was written that sorts through all of the residual turbidity data, and collect all the times at which the turbidity fell in between 47 and 53 NTU. After collecting these values, the algorithm averages the times to obtain the approximate time at which the halfway point of settling occurred. Once the function calculates this value for time, the flocculator height is divided by the average time to obtain the settling velocity. This algorithm came with inherent error in that, in some runs, the turbidity spiked up and down, and either fell into the range prematurely or jumped out of the range when the trend of the data indicated that it should stay within the range.

5.1 Four Clamps

After running the experiments with four clamps, it seems as though smaller orifice size leads to decreased flocculator performance. As shown in 4, it can be seen that trials with 4 mm and 5 mm clamp sizes have lower pC* values at lower dosages. Both the 4 mm and 5 mm configurations have duplicate runs, which are denoted by “dup”. The duplicate 4 mm run is fairly similar to its counterpart, but one of the 5 mm runs is an outlier compared to its counterpart and the rest of the data.

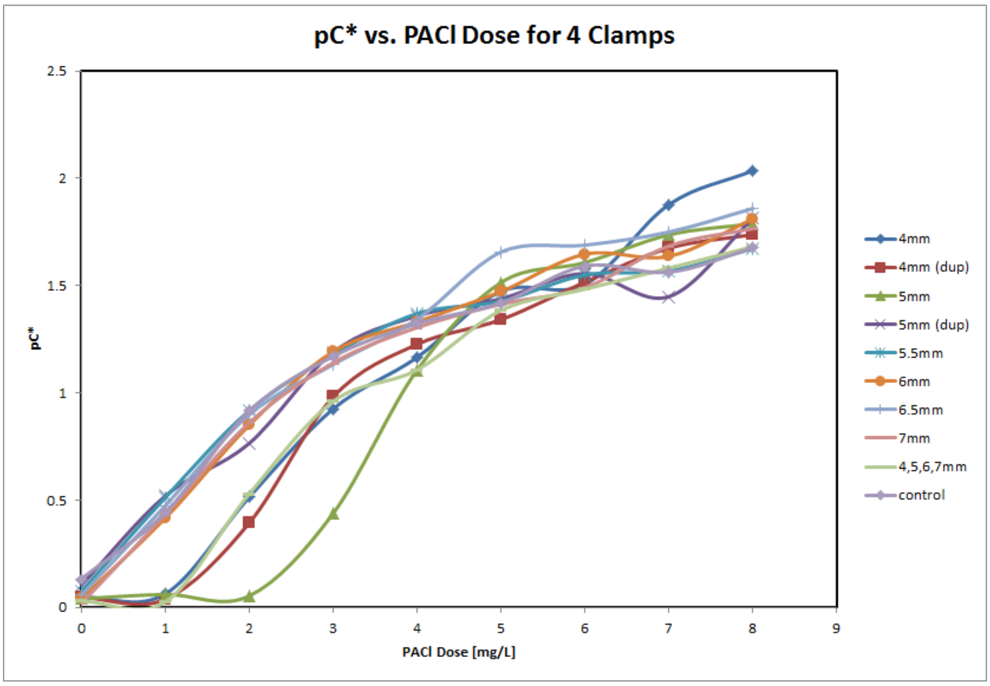

Figure 4: pC* for Four-Clamp Experiments Performed with American PACl

The markedly decreased performance of the one 5 mm run could be accentuated by floc breakup acting on smaller flocs due to low PACl dosages. The lower coagulant and smaller particle size make it more difficult for effective collisions to occur after each break up point. After 4 mg/L, however, the 5 mm curve and the other curves start to follow a similar trend to one another. At this point, it is possible that the flocs, from one breakup point to the next, are able to regain their former size. From this graph, no conclusive arguments can be made about an optimal orifice size, because, at almost all PACl dosages, the pC* values do not follow any trends with respect to their clamp sizes. It is worth noting, however, that the clamp sizes that most frequently had pC* values above the control were the 5 mm, 6 mm, and the 6.5 mm. To say anything conclusive about an optimal orifice size, more experiments should be performed in order to make a clearer distinction between the effects of the different clamp sizes.

A tapered clamp configuration (increasing clamp size) was run in order to see how it might behave with respect to the other four-clamp trials. The curve (labelled 4, 5, 6, 7 mm) fell along both of the 4 mm curves. Because of the limited tapered tube data, though, it is not possible to make any conclusions about how tapering the clamp sizes affects the flocculator. Given that the tapered run conformed to both of the 4 mm runs, a possiblility of the first clamp having the primary effect on the overall performance should be studied upon further research into tapering the tube flocculator.

From 5 and 6, it can be seen that there are few apparent trends within the data.

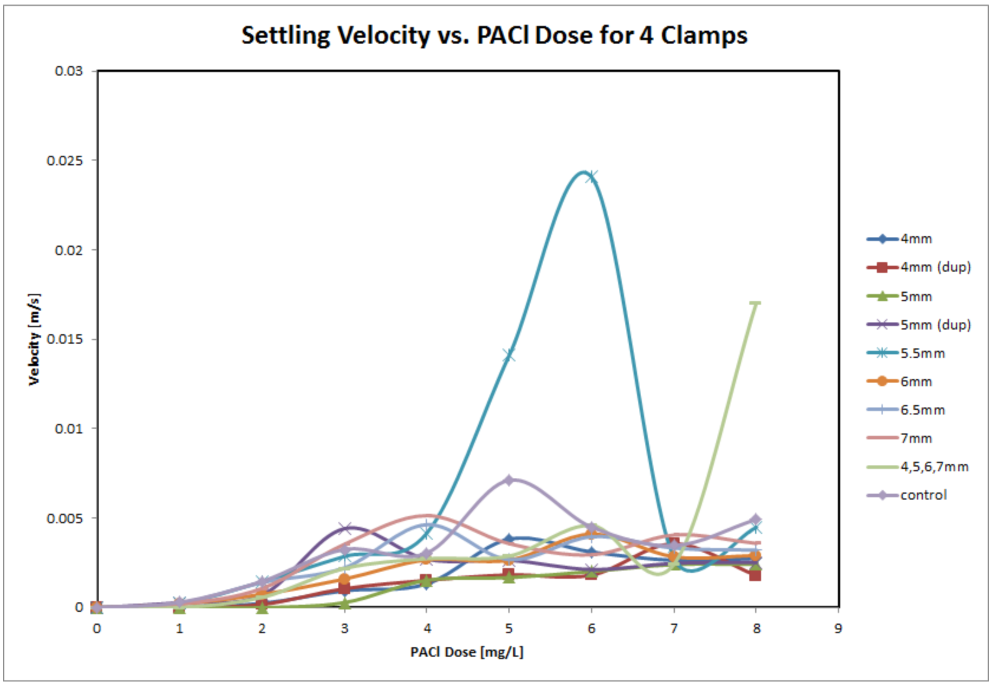

Figure 5: Mean Settling Velocity for Four-Clamp Experiments Performed with American PACl

The curves all behave erratically and spike up and down with little regularity. At 5 and 6 mg/L, however, a larger spike occurs. This is most likely due to error within the algorithm of calculating settling velocity because when the range of accepted values was increased (47-53 NTU to 46-54 NTU) the spikes decreased. This means that a greater range might be more accurate in calculating settling velocity values.

5.2 Eight Clamps

The experiments with eight clamps showed results much unlike those found in the four-clamp experiments. As shown in 7, it can be seen that the larger orifice sizes (5.5 mm, 6.5 mm, and 7 mm) display lower pC* values at the lower doses.

The 4 mm clamps, 5mm clamps, and the control run all display the highest pC* values through all of the PACl Dosages. Even more than the four-clamp experiment, the control run exhibited the most consistently high pC* values. This could indicate that an eight-clamp configuration may initiate excessive floc breakup, and inhibit sufficient floc growth.

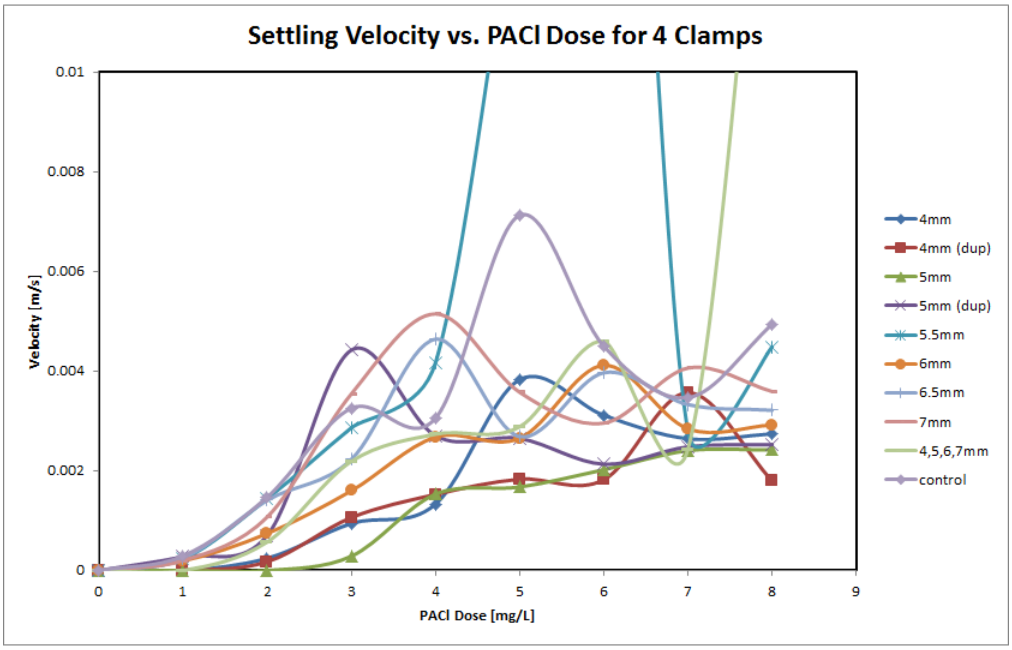

Figure 6: Mean Settling Velocity for Four-Clamp Experiments Performed with American PACl (Zoomed in)

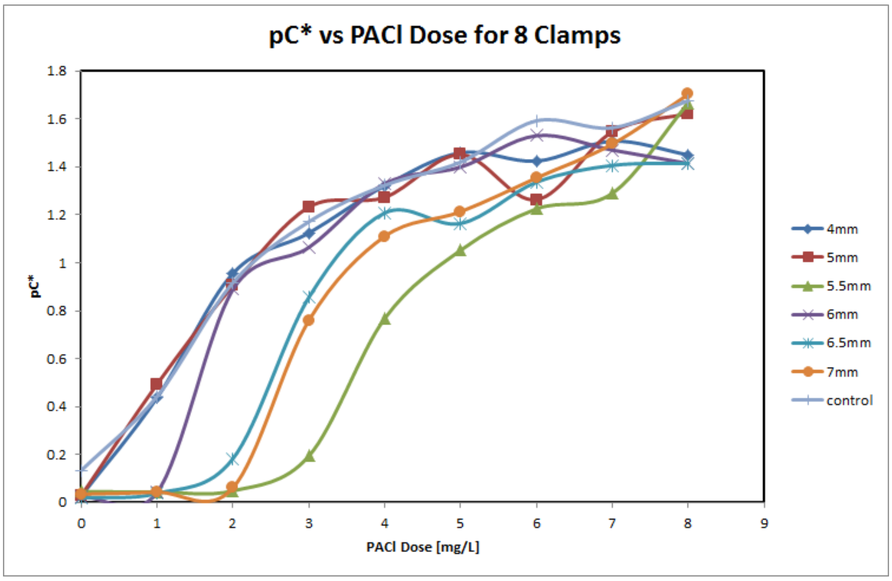

Figure 7: pC* for Eight-Clamp Experiments Performed with American PACl

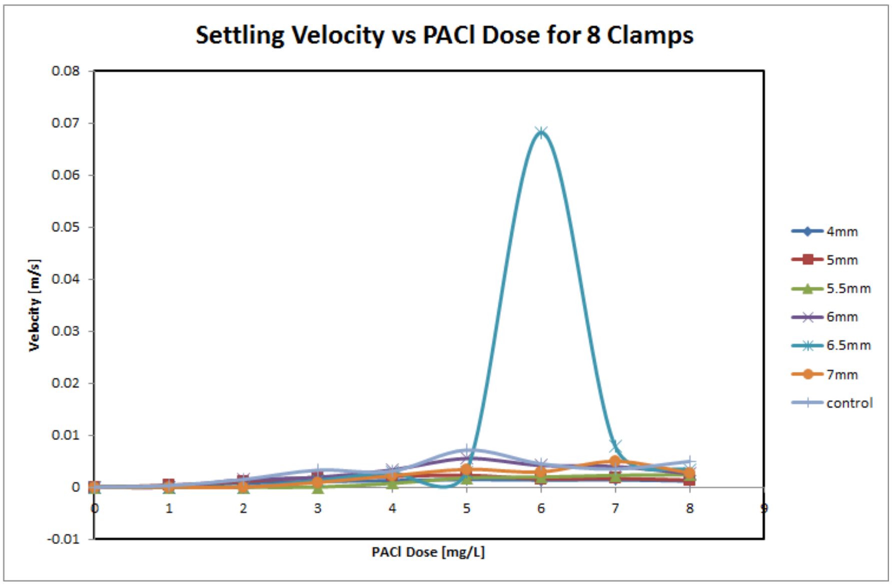

Figure 8: Mean Settling Velocity for Eight-Clamp Experiments Performed with American PACl

From 8, the settling velocities demonstrate a strong trend of settling velocity increasing with orifice size.

Thus, it appears that optimal settling occurs with the least constriction for the eight-clamp configuration. This indicates that eight clamps may, in fact, provide excessive floc breakup, and inhibit the intended overall floc growth.

5.3 Sixteen Clamps

For the sixteen-clamp experiments, only integer-sized clamps were used. Time was allotted for the 5.5 mm and 6.5 mm clamps to be used, but electrical problems prevented these experiments from being completed prior to the end of the Summer 2013 research period. The results of the four integer clamp sizes arranged in a sixteen-clamp configuration compared with a no-clamp control are shown in 10, below.

In the above figure, all of the clamp sizes tended to follow the control, with a little more variation after the 6 mg/L dose. In general, the 4 mm and the 7 mm clamp sizes outperformed the control for doses between 0 and 6 mg/L. After 6 mg/L, the performance of the 4 and 7 mm clamp sizes dropped below the control in removal, while the 6mm and 5 mm sizes rose to perform better than the control. While the performance of these clamp configurations appears to be close, it also appears that the sixteen-clamp configuration is able to improve slightly upon performance of the tube flocculator.

Settling velocities for the sixteen-clamp configuration were plotted against

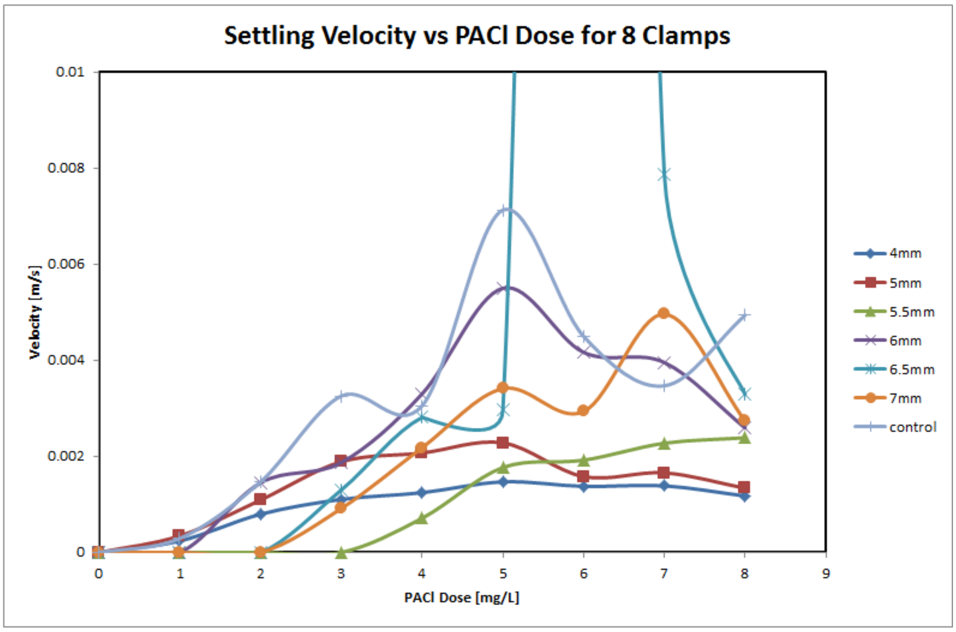

Figure 9: Mean Settling Velocity for Eight-Clamp Experiments Performed with American PACl (Zoomed in)

PACl dosage, and can be seen in 11, below. The data for this experiment follow a definite trend, with settling velocity increasing with constriction size. Thus, the control and the 7 mm clamp set had the highest settling velocities, which indicate larger flocs. The 4, 5, and 6 mm clamp size sets all had lower settling velocities, demonstrating a strong correlation between clamp size and settling velocity. These results may also indicate that the sixteen-clamp configuration reduces the effectiveness of flocculation.

5.4 General Discussion

A possible way to improve future experiments of this nature is to use silicone tubing for the tube flocculator. Silicone appears to be more elastic and regains its original shape after clamping. The Tygon tubing used for these experiments became elliptical in the places where clamps had been placed on it, while silicone tubing remains round after being clamped. This might have affected the control experiment in which we assumed there was no clamping on the tube. If more clamp testing is to be performed, perhaps a switch to the silicone tubing would be useful. Even better would be to find a new material that is both economical and resistant to deformation. A problem with the current coil configuration is that the coils are too closely spaced and have a slight constricting effect on each other at the intersections of the coils. These constrictions may have a

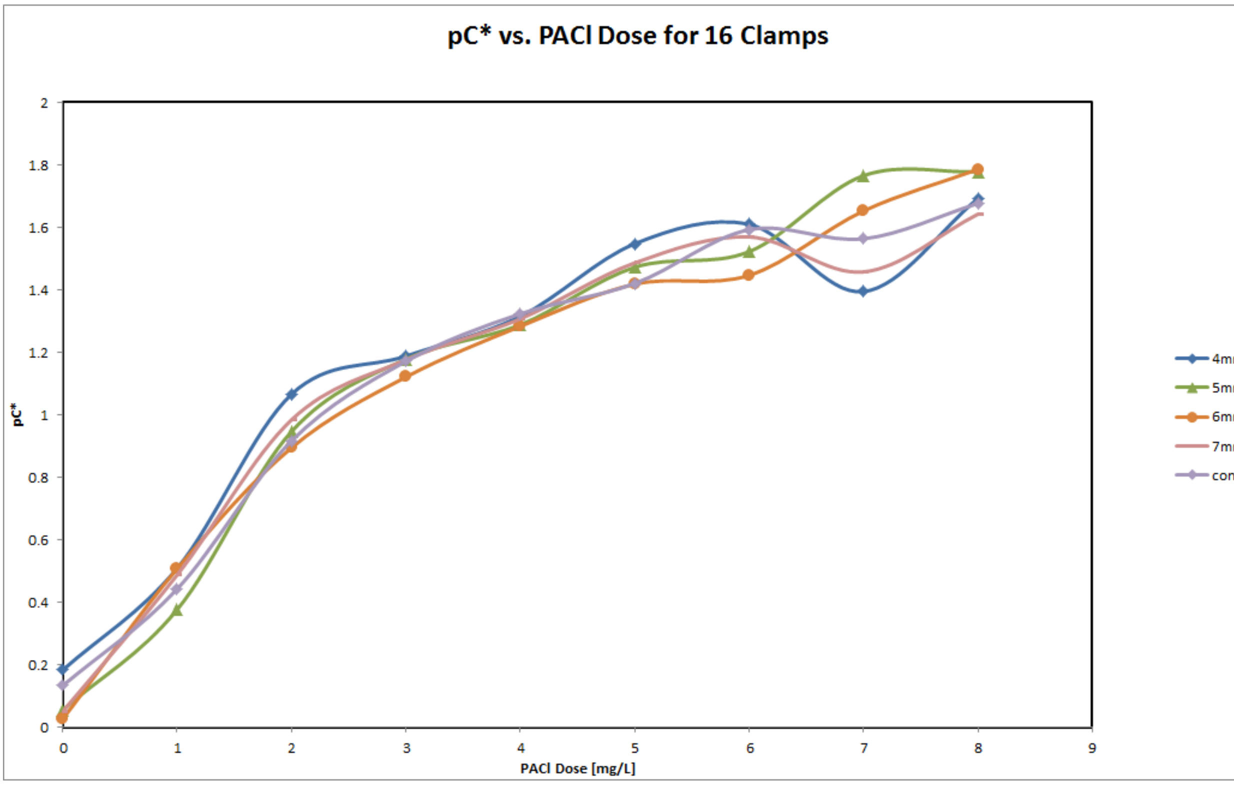

Figure 10: pC* for Sixteen-Clamp Experiments Performed with American PACl

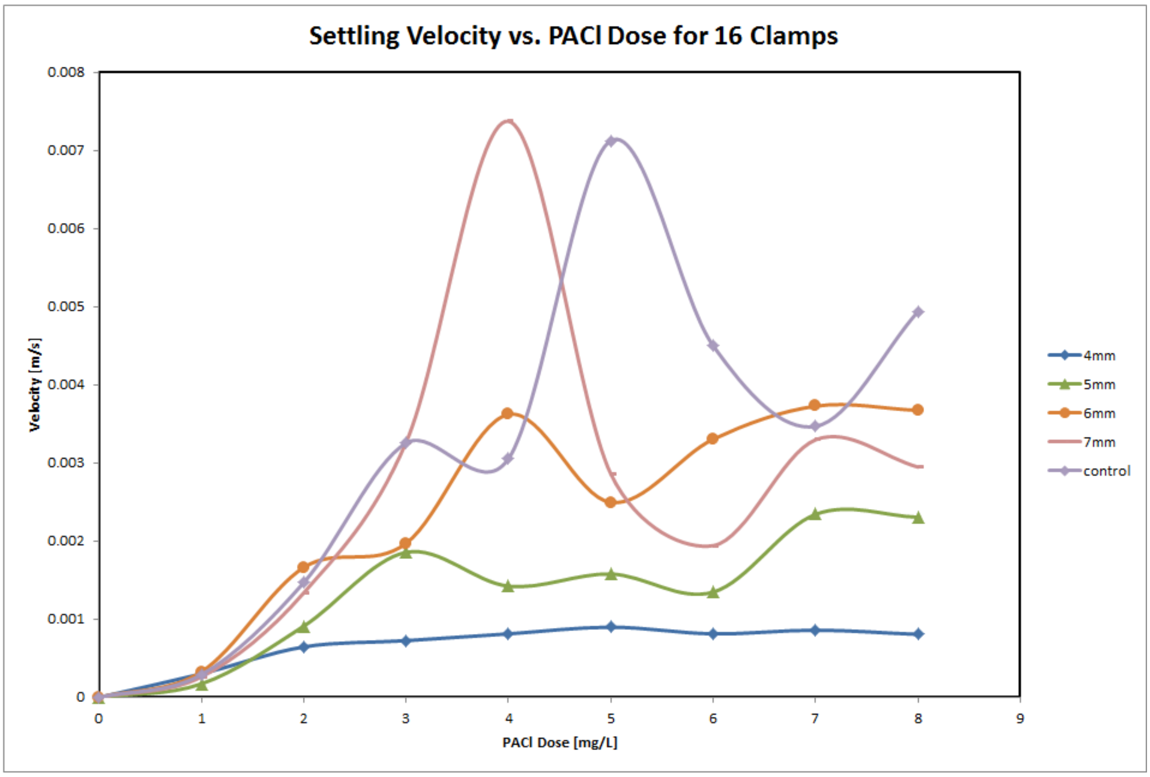

Figure 11: Mean Settling Velocity for Sixteen-Clamp Experiments Performed with American PACl

minor floc breakup effect of their own. Longer tubes would make for more room to coil, and would prevent this effect. Another issue to address would be the algorithm to calculate settling velocity. If smoothing the curve prior to running the halfway settling time function were possible, it would greatly reduce the error in the function. A very important improvement that could be made to the experimental apparatus would be to eliminate the electrical problem that causes the ground fault interrupter to trip and cut power to the setup. For each of the times that this happened, it occurred during the settle state. This could be a coincidental trend, as the settle state is long, and there is a higher probability of any event occurring during the settle state than during any other state. There is reason to believe, though, that this is not random. One hypothesis is that the ball valve, which is continually oscillating during settle state, may be causing the ground fault interrupter to activate. Future work should explore this hypothesis, and seek to resolve the problem with the electrical components of the system, as well as the ball valve. As a final recommendation, the experiments outlined in this paper should be repeated multiple times and compared. As there were some outliers (especially the difference between the two 5mm runs for four clamps), it seems that there is a significant amount of random error associated with these experiments. Further testing would give greater insight into general trends, allowing researchers to reject outlying values, and find reasonable average values. Before this is done, it is difficult to make solid conclusions as to the optimal orifice size.

Part V
Conclusions

The results of the end clamp testing experiments showed a general trend of decreasing residual turbidity with increasing clamp size. This suggests that the large flocs that formed through the 28 m of the flocculator will break up into smaller particles as tighter clamps are applied. This follows in accordance with the trend of higher energy dissipation rates for tighter clamp sizes.

Possible reasons for the poor performance of the Honduran PACl compared to the American PACl are inactivity due to coagulation during storage, incorrectly assuming the Honduran PACl was pure, or simply a weaker activity than the American PACl.

Based on the multiple-clamp experiments, a number of tentative conclusions can be made. For the four-clamp experiment, the experimental (clamped) runs appeared to outperform the control after a concentration of about 5 mg/L. For future work, it would be valuable to extend the dosage range to higher doses (perhaps 0-10 mg/L), so as to confirm that the clamps are indeed beneficial in the four-clamp configuration. From this study, it does appear that a four-clamp configuration with the right orifice size (from this experiment: 6 mm, 6.5 mm, and 7 mm) will increase flocculation efficiency. At this point, it appears that an eight-clamp configuration will not substantially improve flocculator performance. This is confirmed by the settling velocities for this test, which decreased for every increase in constriction. For the sixteen-clamp experiment, it seems that 7 mm and 4 mm clamps are more effective than the no-clamp setup at a coagulant dose between 1 and 5 mg/L. After 6 mg/L, the 5 mm and 6 mm clamps appear to perform better than the no-clamp configuration. Further testing at higher dosages would be useful in confirming or disproving this and the other trends suggested in this paper.

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