Rapid Mix Contact Chamber, Spring 2017

Philip Akpan, Karin Teuffer, Grace Zhang

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Abstract

In water treatment, a portion of the coagulant may not attach to the influent particles, requiring a higher dose than theoretically needed for flocculation. Initial experiments confirmed that straight tube flocculators work as a measure of free coagulant, relating higher headloss to coagulant lost to the walls. However, the presence of clay was found to not affect headloss. Thus, a new contact chamber was designed to increase the ratio of total clay to tube surface area. The experiments showed that a ratio of 1 is enough to mitigate the total increase of headloss for 0.6 and 1.0 mL/s flow rates at 50 NTU.

Introduction

Rapid mix and flocculation are important processes in providing safe drinking water as they are essential to the sedimentation of particles in the influent water. Rapid mix ensures coagulant is thoroughly mixed through turbulence, and flocculation provides energy dissipation points that increase contact between particles and the coagulant's nanoclusters. Eventually this progresses to floc formation, large clusters of unwanted particles and coagulant, which enhances settling in subsequent water treatment steps (Letterman et al., 1973). Building on this knowledge, previous and current rapid mix contact chamber teams developed the goal of reducing free coagulant. The term referred to nanoclusters that did not immediately attach to particles and therefore did not aid in early floc formation. Instead, this coagulant was more easily held on the walls of the flocculator. Defining where exactly and under what conditions the coagulant attached was vital to determining precise coagulant doses for varying flow rates and turbidities. More accurate measurements translate to less money spent unnecessarily per time unit of operation. Precise knowledge on the mechanism of attachment can lead to efficient flocculation with no free coagulant present, thus eliminating the need to account for lost coagulant and reducing the total amount applied. A smaller amount per day, means lower bulk amounts purchased per year and a lower overall investment required.

Thus, the Spring Zu et al. (2016) and Fall Krishnamoorthysujatha et al. (2016) 2016 teams worked on developing a method to measure whether and how much coagulant is deposited on the walls of the flocculator. The spring 2017 Rapid Mix Contact Chamber team continued studying the effect of deposition on head loss through the flocculator as well as the benefits of incorporating extra contact time through a chamber. To begin the analysis, the focus was on replicating the trials of the Fall 2016 team to understand the coagulant-headloss relationship. The next step was testing the effect of the clay particles on the headloss in the flocculator. Results obtained by the Fall 2016 team stated the possibility of clay reducing the headloss significantly due to shear forces scraping the coagulant off the walls. The current team conducted experiments that ran influent raw water and coagulant first, to allow the coagulant to stick to the walls of the flocculator. Then, clay, water and coagulant were run simultaneously to see whether the clay would scrape off the accumulated coagulant. There were also experiments in which all three components were run at the same time to evaluate whether the clay could prevent the coagulant from sticking to the walls in the first place. The results differed significantly from Fall 2016's in which clay reduced the headloss as soon as it was introduced. From the conclusions derived from this semester's results the contact chamber design was rethought to give the clay and coagulant a better opportunity to attach to each other. The hypothesis that the mere presence of clay easily and rapidly eliminated built up coagulant was modified to state that clay helps reduce free coagulant when the total surface area of the clay in the flocculator is greater than that of the flocculator itself. Thus, the flocculator headloss relationship with coagulant attachment works even when clay is present, ensuring that the system works as a free coagulant detector when working with turbid water. This means that the RMCC team can test free coagulant attachment under more realistic conditions, with different turbidities, and improve the design of a contact chamber to increase the ratio of clay to plant wall surface area. An effective contact chamber would reduce the cost of coagulant and reduce the total running cost of an AguaClara plant. One of the main goals of AguaClara is to provide inexpensive water treatment. Reducing the cost in any step of the process is therefore beneficial.

Literature Review

The research that has been done on rapid mix processes is prevalent mainly for mechanical systems. However, there are results that are relevant to AguaClara plants. For example, Letterman et al. (1973) suggests that the velocity gradient (GR) should be larger for shorter contact times during rapid mix. That is, a G of 1000 s-1 for 20 seconds of residence time. This parameter is also used in the rapid mix contact chamber team's research as a way to measure the effect of shear between large and small particles, and hence their attachment to form larger flocs. Research presented in the International Conference on heat transfer, thermal engineering and environment by Tzoupanos (2008) includes topics closer to AguaClara's focus including the difference between micro and macro flocculation. This is related to the way particle aggregation is successfully attained either through thermal motion or "inducing velocity gradients". Specific to this research, the value of G can affect the contact chamber that would be placed between rapid mix and flocculation. Residence time was also considered an important parameter this semester to vary experimentally. The goal was to determine how much extra time would result in an increase in flocculation successes.

Another benefit of rapid mixing is the decreased loss in coagulant. Vrale and Jorden (1971) stated that the when rapid mixing is not designed well it can result in chemical waste and slower floc production. The team considered both topics, as coagulant loss results in greater quantities added which translates to higher yet potentially unnecessary costs. Their paper focused on agitators and baffled basins but they also presented the topic of where the optimal location of coagulant addition is. In their case, application near the blade of the mechanical agitator seemed to be more effective.

Other aspects of rapid mix that have been studied within AguaClara and beyond include the mechanisms of coagulant attachment or coverage of particles. The zeta potential is commonly used to show whether the coagulant is effective by measuring the charge on the surface of particles in the flow (Vrale and Jorden, 1971). There are studies that show that the zeta potential should be at 0 to prevent particles from repelling each other. However , research at Cornell has shown that a probable hypothesis is that the "intermolecular polar bonds between the oxygen and aluminum are stronger than intermolecular polar bonds between oxygen and hydrogen" (Weber - Shirk , 2016). In addition, the topic of changes in the influent water source may unveil insights on coagulant mechanisms. Dentel Dentel (1991) suggests that there are also temporal variations that affect how effective the coagulant is in attaching to and removing particles in the flow. "A recent survey of 35 water treatment plants showed that influent turbidity could vary by orders of magnitude at a given plant". This all affects the ultimate best dose of coagulant required.

Previous Work

Testing of the effect of coagulant loss on the flocculator walls originally began with a mass balance approach and log relationship of change in turbidity (Zu et al., 2016). However, the Fall 2016 team followed more current experimental results which related headloss to coagulant build up .

The Fall 2016 team explored how the headloss in a specifically designed flocculator responded to a change in tube diameter, due to attachment of coagulant nanoclusters on the walls (Krishnamoorthysujatha et al., 2016). They conducted several tests with different flow rates to determine the threshold for coagulant build up - a flow rate with noticeable headloss - so they could subsequently analyze the effects of adding clay to the flow. The purpose was to test water with different turbidities to determine how effectively it removed any coagulant that had accumulated. They used a straight-tube flocculator in order to prevent deposition of clay particles while still allowing nanoclusters of the coagulant to collect on the wall. Below is an example graph from the Fall 2016 team's final report. It represents an immediate drop in headloss through the flocculator once clay was added to the flow. However, they only had time to collect data from one trial and did not include numerical analysis on how significant the impact was. This offers the basis for the current team's continued efforts in repeating the same experiments .

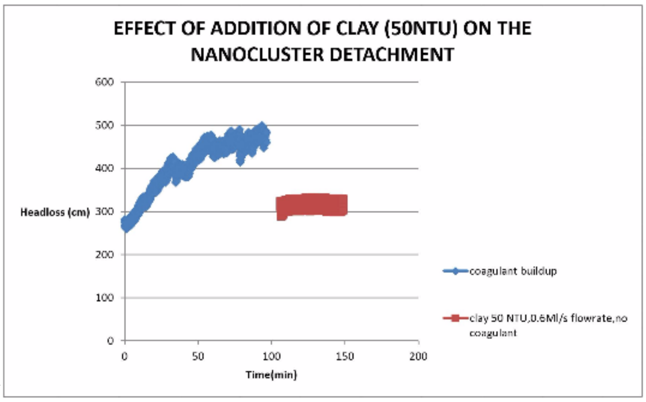

Figure 1: The plot represents the effect of the addition of clay (50NTU,0.6mL/s flow rate) on headloss through the flocculator after coagulant (0.051mL/s flow rate) buildup. The portion of data in blue represents only the flow of water and coagulant through the system. As displayed, the headloss increased significantly as coagulant attached to the walls. The red portion represents the headloss values once clay was added to the system. The immediate drop in headloss to a constant value showed that the clay prevented any further attachment of coagulant.

The effect of adding a contact chamber was also tested. The team designed one with a length of about 0.5 meters and a diameter of 0.5 inches. Placed between the point of coagulant and water contact, and the flocculator, it was hypothesized that the chamber would aid in reducing free coagulant. Hence, coagulant loss should also decrease. The results showed no clear advantage of using a contact chamber as the clay (5 and 50 NTU) and flow rate (0.6 mL / s) it was tested with did not seem to allow coagulant build-up in the first place. This year, the Rapid Mix Contact Chamber team continued analyzing coagulant loss by headloss changes. The first step was to continue using last semester's straight flocculator and contact chamber and replicate their experiments, to define a clear conclusion on the impact of clay particles on the coagulant build-up. After analyzing the impact of clay on the reduction of headloss, the team worked on designing a new coiled flocculator and contact chamber to further analyze the influence of the latter .

Methods

Experimental Apparatus

The Spring 2017 Rapid Mix Contact Chamber team started by replicating and validating the experiments conducted by the Fall 2016 team.

- Set up

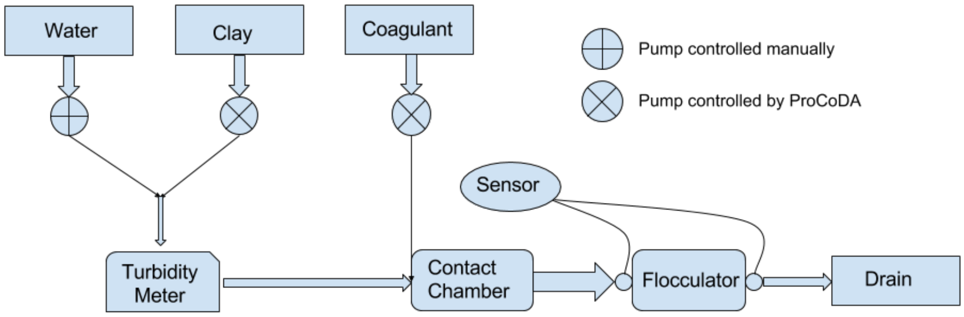

Figure 2: Schematic Representation of the setup . The water comes into the system from a feeding tube connected to the lab's tap water supply. This tube is then connected to the water pump which drives the water through the rest of the system. A clay solution is pumped through the clay pump and mixed with the water before entering the contact chamber. The clay and water mixture then goes through the turbidity meter. The coagulant is then injected into the system right before entering the contact chamber, and then flows through the flocculator where a pressure sensor monitors headloss through the entire tube. The fluid finally exits the system and flows through the drain. Note: When the contact chamber is not included in the system the water and clay mixture, and the coagulant come into contact right before entering the flocculator. In addition, the schematic and connections between components are identical for later experiments using a coiled flocculator .

The following image in Figure 3 represents the complete set up for experiments, including the old contact chamber .

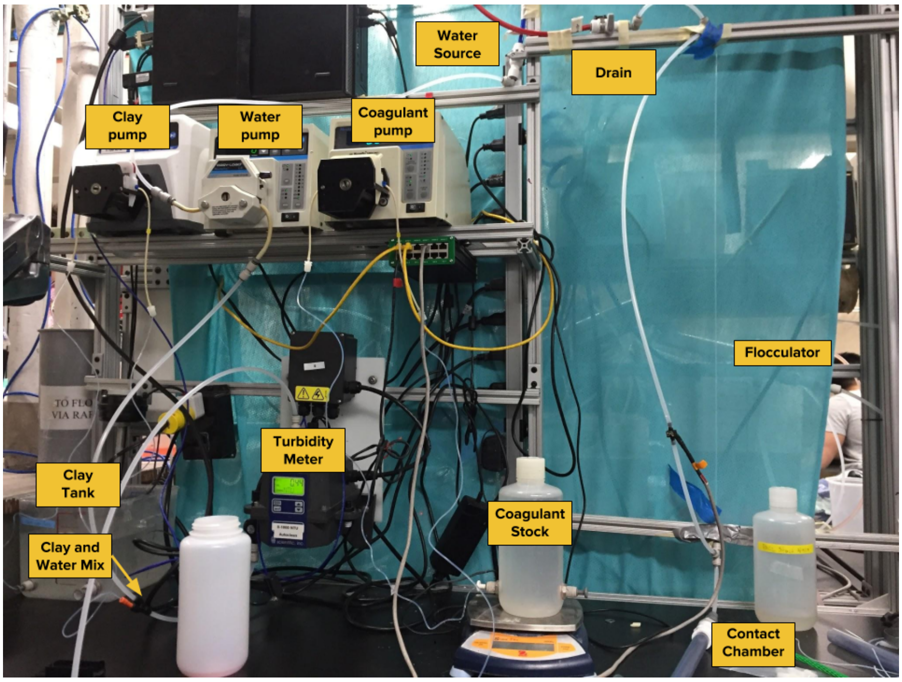

Figure 3: Apparatus setup in the lab. The influent water enters the system from the pipe labeled source and flows through the water pump. It then mixes with the clay solution, which also goes through its own pump, and enters the contact chamber (not shown) before flowing up the flocculator and out the waste pipe. The coagulant is pumped as well and is added to the flow right before entering the contact chamber .

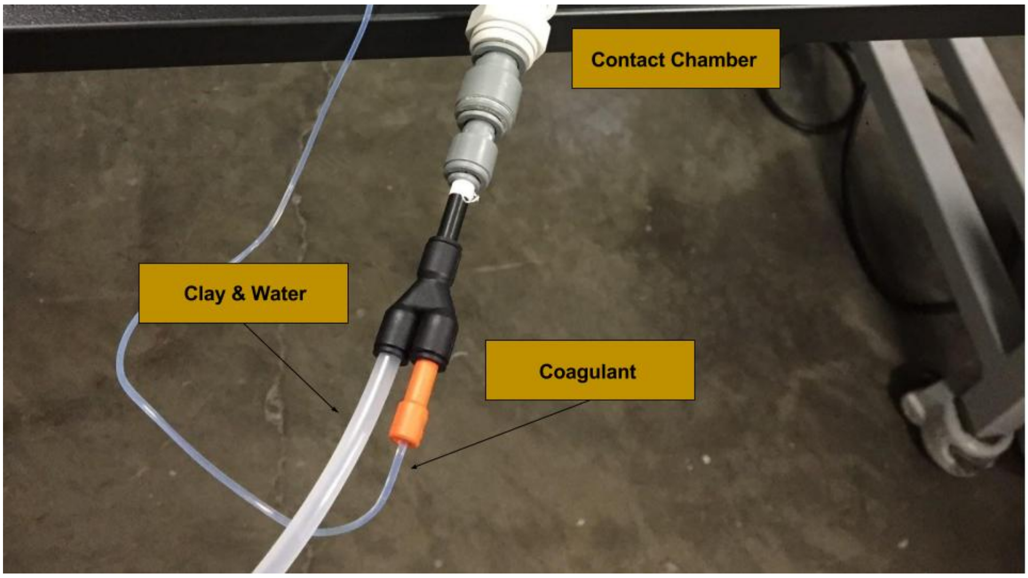

Figure 4: Picture showing how the clay, coagulant, and water flow into the contact chamber. The coagulant is mixed with the influent water and clay upstream of the contact chamber to ensure that flocculation does not start in the connector tubing beforehand.

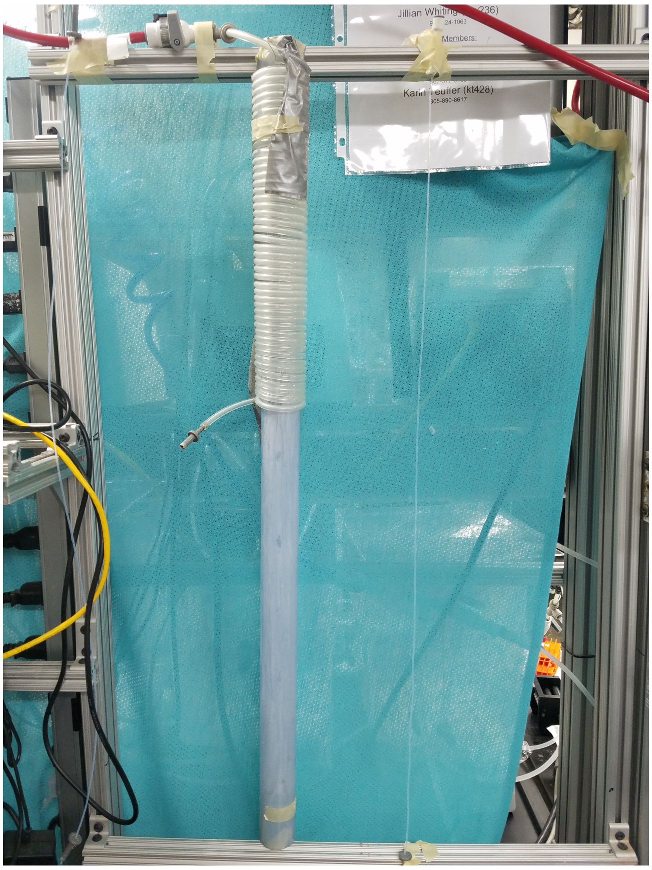

Figure 5: Picture showing the coiled flocculator. The flocculator was made out of clear, flexible tubing and was designed to have 50cm of headloss and a residence time of 1 minute given a flowrate of 1 mL/s.

- Complications in construction: In Fall 2016, Krishnamoorthysujatha et al. (2016) designed and built a straight tube flocculator out of flexible 1.35mm diameter tubing, and a contact chamber out of hard plastic 13 mm in diameter. The current team decided to repeat their experiments to acquire more data on coagulant and clay interactions when flowing through just the flocculator as well as when the contact chamber is added. The obstacles in the replication were due to the change from size 13 tubing (0.8 mm in diameter), for the coagulant and clay pumps, to blue-yellow tubing. This caused a slight modification in the calculations for pump flow rate and RPM. In addition, some connections in the contact chamber had to be replaced to prevent leaks.

Procedure

The following subsections separate the steps taken in running the physical apparatus and those for designing the flocculator and contact chamber . Both sets of procedures come together to allow the smooth running of experiments that test for head loss changes across the flocculator. One type of experiment allows coagulant and water to flow through the system while the other includes coagulant, water and clay .

Operational Procedures

In order to better compare the data generated by the team's experiment and last semester's experiment, all the experiment were run with 5NTU or 50NTU clay solutions as a representation of high and low turbidity conditions. The effect of clay and turbid water was tested subsequently, with and without the contact chambers.

Note: The detail of the set points is included in this report's appendix, along with a sequential list of the experimental steps and sample parameters.

Design Procedures

The design procedures involve the steps and decisions taken when building and redesigning the flocculator and contact chamber. One of the goals of this semester was to reduce the head loss of the former to 50cm and achieve a residence time of one minute. Thus, a coiled tube flocculator was chosen as the preliminary base design. Referenced MathCAD files in Fall 2016's report were accessed as an aid.

The equations below refer to the design of the coiled flocculator . The assumed parameters for the basis of the design were a flow rate Q of 1.0 mL/s, a Gθ goal of 20000, a tubing diameter, D, of 3.25 mm (0.128 in), a radius of curvature, Rc, of 2.65 mm (0.813 in), and roughness of PVC ϵ of 0.12mm. Note: Re refers to the Reynolds number.

$$h_f = f * \frac{8}{g * \pi^2} * \frac{LQ^2}{D^5} \tag{1}$$

$$De = \sqrt{\frac{D}{Rc}} Re \tag{2}$$

$$h_{friction} = h_f * (1 + 0.033 log(De)^4) \tag{3}$$

$$\epsilon_{floc} = \frac{h_{friction} g}{\theta} = 77.36 \frac{mW}{kg} \tag{4}$$

$$G_{floc} = \sqrt{\frac{\epsilon_{floc}}{\nu}} = 278.141 \frac{1}{s} \tag{5}$$

$$\theta_{goal} = \frac{G\theta_{goal}}{G_{floc}} = 1 min \tag{6}$$

$$L_{Floc} = \theta_{goal} \frac{Q}{Area} = 7.227 m \tag{7}$$

The contact chamber used initially was the one designed by the Fall 2016 team. It was built with a PVC pipe of 0.5 m in length and 13.2 mm in diameter. After preliminary results showing that the addition of clay did not reduce the rate of headloss, the team decided to test the contact chamber vertically. This allowed for full pipe flow, increasing the ratio of clay surface area to that of the contact tube's surface area. The team hypothesized that this would enable greater contact between clay and coagulant particles.

In designing a contact chamber, the surface area of the clay with respect to the surface area of the contact chamber should ideally be greater than or equal to one. This is because coagulant sticks to all available surfaces, so creating a favorable situation for coagulant to attach to particles should increase flocculation efficiency. Therefore, when designing the new contact chamber, the team used the ratio of clay surface area to contact chamber surface area as a dimensionless design parameter. The team considered the shape clay particles as spheres and the shape contact chambers as cylinders when calculating the surface areas. In addition, the team modeled the particle parameters after clay used in the lab. Therefore, the team assumed 1 NTU = 1.7 mg/L, a clay density of 2450 kg/m^3, a clay diameter of 4 μm, and a spherical clay shape. It has a length of 0.203 m and a diameter of 76 mm.

$$Ratio_{SA} = \frac{Total_{SAClay}}{SA_{tube}} = 0.991 \approx 1. \tag{8}$$

Results and Analysis

The team ran an experiment with coagulant and water in order to test the effect of coagulant attachment to the walls of the flocculator on headloss. Figure 6 below shows the relationship between headloss and coagulant attachment through time. The longer the experiment was run for, the higher the quantity of coagulant attached to the walls and the higher the headloss. The plot shows that this follows an approximate logarithmic relationship.

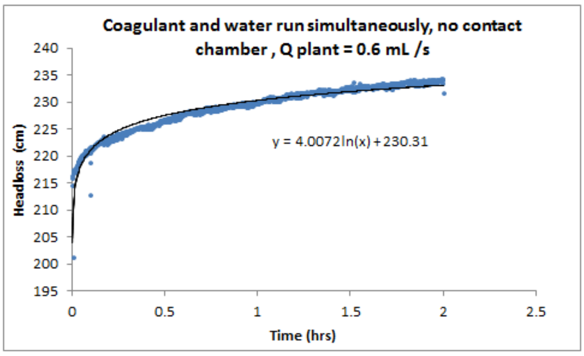

Figure 6: The sustained increase in headloss through time shows an increase in coagulant attachment. This served as an initial check that the Fall 2016 team's use of the relationship between headloss and attachment matched this semester's results.

The experiment described in Figure 6 was repeated as shown in Figure 7. However, the raw water was run through for some time before the coagulant pump was turned on. This point in time is shown as the immediate jump in head loss at 0.07 hours. The subsequent fall in head loss at 0.4 hours occurred when the coagulant pump was turned off.

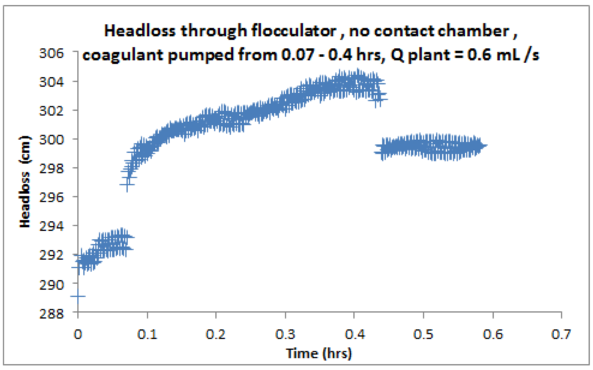

Figure 7: The first experiment was rerun but the raw water was pumped without coagulant at the beginning and end of the total run time to show the immediate drop in headloss when the coagulant is shut off. This further supports the idea that coagulant flowing through the flocculator will attach to the walls and cause an increase in headloss

The initial jump is hypothesized to be due to two factors. The first is that the increased flow rate from pumping the coagulant causes an instantaneous increase in the head loss. The second is that as the coagulant reaches the flocculator entrance, some of it immediately attaches to the walls and causes a larger minor loss from the decrease in diameter. The drop in headloss after coagulant injections were stopped is similar to that mentioned in (Krishnamoorthysujatha et al., 2016), but in contrast to last semester's results it did not return to the original value measured at 0 hours.

Figure 8 is a comparison between the data generated by the Spring 2017 and Fall 2016 rapid mix contact chamber teams. Both teams got similar results, with an increase in headloss due to coagulant deposition over time. Although the data from the Fall 2016 team shows a linear increase in headloss (Krishnamoorthysujatha et al., 2016) and the data from spring 2016 team has an approximate logarithmic trend, they both proved the point that the straight tube flocculator can be used as a detector of free coagulant. It is possible to estimate the amount of coagulant attaching to the wall by measuring the headloss of the flocculator. The differences in variance in the headloss are due to the pressure sensor sensitivity and how often the values are recorded. It does not, however, affect the general trend discussed.

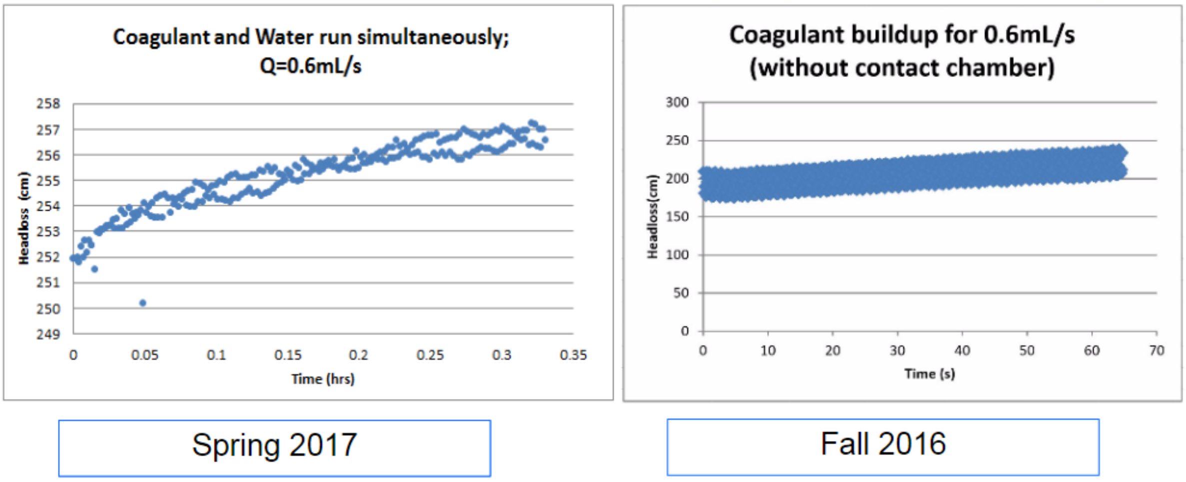

Figure 8: The plot on the left is the result of a second experiment similar to that shown in Figure 6. It proves once again that headloss increases over time when coagulant and water are run simultaneously. Additionally, it shows that it it is similar to the Fall 2016 results. The main difference is the magnitude of the total headloss increase.

To replicate and validate the Fall 2016 team's experiments, the next step was to determine a threshold flow rate in which coagulant would not attach to the flocculator walls. Figure 9 shows a comparison between headloss when the flow rate is 1.0 mL/s, shown in red, and 1.6 mL/s, shown in green. At 1.0 mL/s, there was still a significant increase in the headloss when coagulant flowed through the flocculator. However, once the flow rate was increased to 1.6 mL/s, there was no increase in headloss, which means that the coagulant was not attaching to the walls of the flocculator. Thus, it was concluded that the threshold flow rate for an effect on headloss is between 1.0 and 1.6 mL/s. As in previous plots, the jump in the graph simply results from the increased flow rate due to addition of the clay solution. With an understanding of the threshold flow rate, the later experiments were all conducted with a 0.6mL/s and 1mL/s flow rate.

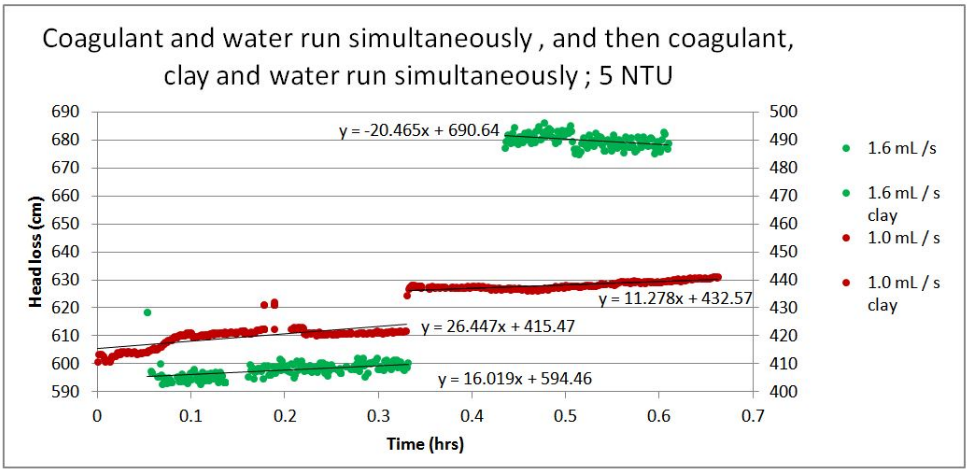

Figure 9: Focusing on the first half of the experiments (before the headloss jump caused by the clay flow rate), the 1.6 mL/s flow rate was too high for large amounts of coagulant to stick to the walls. This is represented by the smaller slope when compared to the 1.0 mL / s flow rate (red series). In the second part, when clay was added, the 1.0 mL/s flow rate still shows a small slope, while the green series yields a constant decline in headloss. Note: the 1.0 mL/s flow rate is plotted on a secondary axis but the intervals for both flow rates are equal (5 cm).

After developing a deeper understanding of coagulant deposition on the walls of the flocculator and concluding that the tube flocculator can be used as a detector of free coagulant, the team continued by testing the effect of clay on the coagulant deposition. Unlike the results generated by the Fall 2016 team (Krishnamoorthysujatha et al., 2016), the Spring 2017 results show that the clay does not significantly decrease the headloss within the flocculator. Figure 10 shows that in the Fall 2016 report the headloss immediately decreased to the original value with the addition of clay, while the Spring 2017 team found that the headloss continued to increase. The reason for the stark difference in results is not yet clear. Note that the increase of headloss in the graph on the left happened even after there was no coagulant running through the system, which means it was due to either the increase in flow rate from the clay solution or due to the clay sticking to the coagulant on the walls.

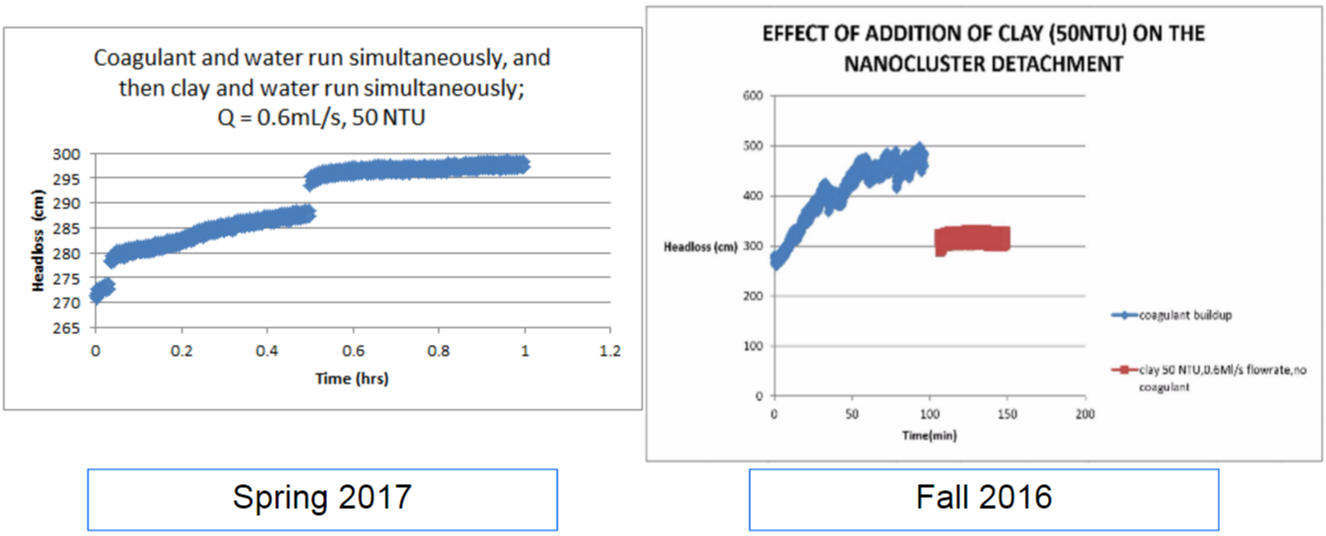

Figure 10: At 0.5 hours the plot on the left depicts the addition of clay into the system with no coagulant. This point corresponds to the beginning of the red line in the plot on the right. The plot on the left shows that the rate of headloss increase when clay was added was lower than when coagulant was running through the system. The plot on the right shows that the with the addition of clay, the Fall 2016 team witnessed an an immediate drop in headloss to a constant value.

The team ran more experiments with the clay solution but ran coagulant, clay and water simultaneously, rather than coagulant and clay separately in time. Figure 11 shows the results generated with different flow rates. The chosen turbidity was 5 NTU to compare to previous cases. In both plots the headloss continued to increase despite the presence of clay. The reason is that coagulant was still running through the system, and the clay did not seem to have any effect on decreasing its deposition onto the walls of the flocculator.

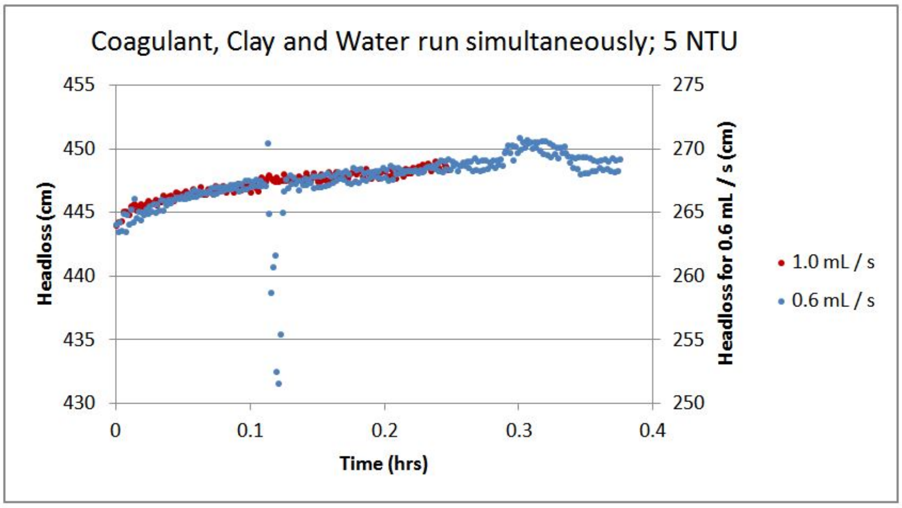

Figure 11: Similar to past experiments, the headloss continued to increase even after clay was added. Note that although the headloss for 1.0mL/s flow rate is around 265cm to 270cm while the headloss for 0.6mL/s is around 445 to 450, the slopes are still similar for these two flow rates as indicated by the graph. This may indicate that under the threshold value at which coagulant is flushed out, coagulant deposition may be independent of flow rate. Note: the 0.6 mL/s headloss values are plotted in a secondary axis but the intervals for both axes are displayed at 5 cm.

The team ran a final experiment with the same flow rates as in Figure 11 but with a turbidity of 50NTU. Figure 12 depicts both stages of the experiment (with and without clay) and shows that the results were the same as for a turbidity of 5 NTU. It is evident that there was a similar constant increase in headloss before and after the clay was added. However, in the same amount of time, the headloss for the 1.0 mL/s flow rate increased more than that of the 0.6 mL/s flow rate in both parts of the experiment. The pumps are specifically programmed to maintain a constant concentration of coagulant in the plant despite running it at different flow rates. The higher flow rate, however, is associated with a higher mass flow rate of coagulant through the flocculator, causing the coagulant to build up faster and thus increase the headloss.

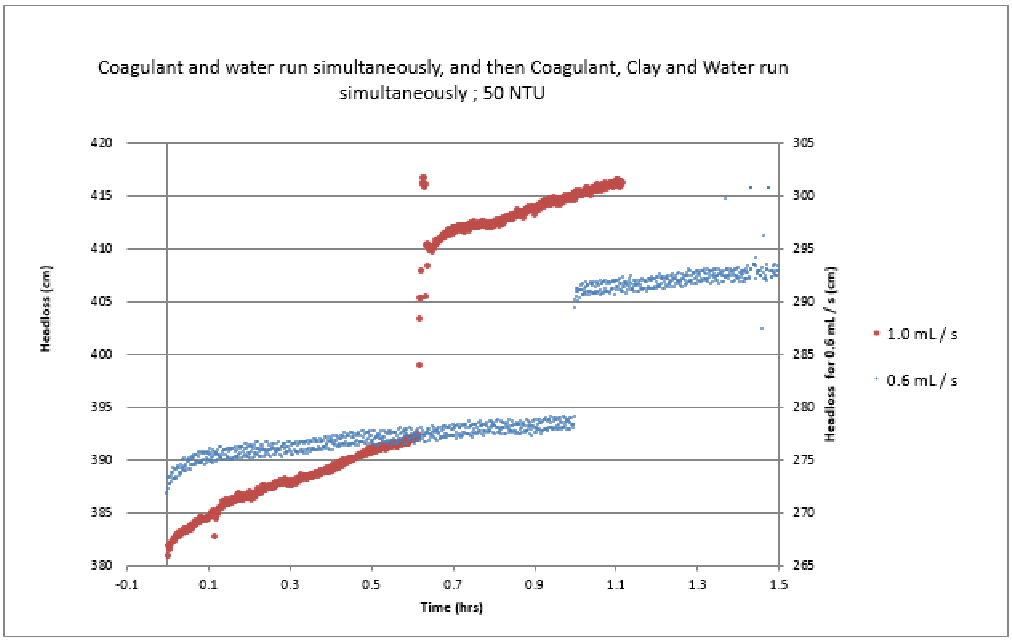

Figure 12: The turbidity of 50 NTU proved that even at higher concentrations of clay, coagulant is still able to stick to the walls. The blue series, representing a 0.6 mL/s flow rate is plotted on a secondary axis, but the comparison with the 1.0 mL/s flow rate in red is still easily visualized because the intervals of each axis are equal (5 cm). Evidently, the 1.0 mL/s flow rate causes a faster increase in headloss in both sections of the experiment.

The results support the hypothesis that coagulant will increase headloss by attaching to the walls of the flocculator and that flow rates beneath a certain value, in this case between 0.6 mL/s and 1.6 mL/s have a similar effect on the headloss. The results also show that the clay particles do not have a significant impact on the coagulant deposition. The hypothesis introduced at the beginning of the report is derived from these results. It states that the coagulant particles have a very low probability of attaching to the clay particles when the total surface area of all clay particles in the flocculator at a given point in time, is much lower than the surface area of the flocculator. From preliminary calculations the ratio of total clay particle surface area, at 50 NTU, to flocculator surface area was $5X10^{-3}$. The ratio for the contact chamber was 0.172.

To adjust for better flocculation, the new contact chamber was designed with a value very close to 1. Its clay to tube surface area ratio is 0.991.

Figure 13 shows the effect of both the old and new contact chambers with a flow rate of 0.6 mL/s and a turbidity of 50NTU. The old contact chamber values, shown in blue, display an immediate increase in headloss and then a drop that leads to a more constant value. The new contact chamber does the opposite, decreasing headloss starting at time = 0 hours and continuing to decrease it throughout the experiment. This comparison resembles that of Figure 9 in which the threshold flow rate showed a constant headloss due to its prevention of coagulant build up.

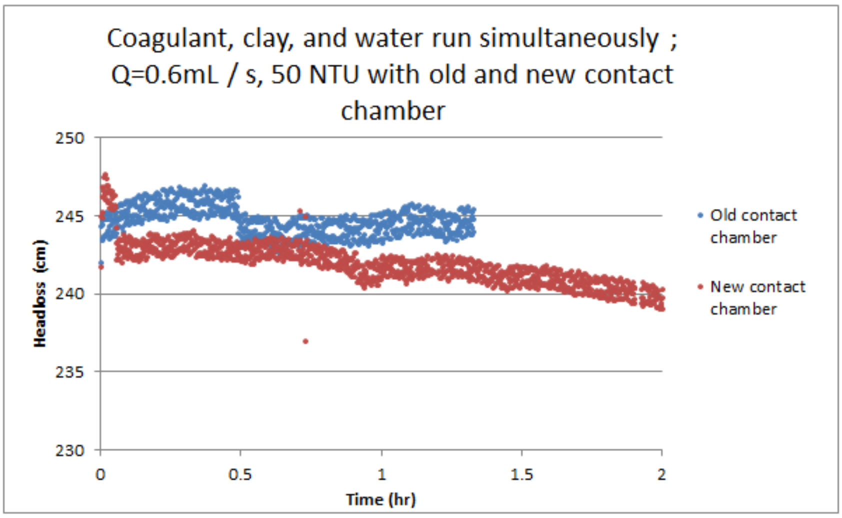

Figure 13: The blue series represents the headloss when running coagulant, clay and water through the system with the old contact chamber (designed by the Fall 2016 team). The red series represents the headloss values recorded from an experiment with the same parameters but with the new contact chamber. The old contact chamber was less effective at preventing coagulant build up, while the new contact chamber maintained a more steady decrease in headloss.

The next experiment was completed with the same parameters as those in Figure 13 but with a flow rate of 1.0 mL/s. The old contact chamber shown in blue again displays an immediate increase in headloss. This also occurred in a smaller amount of time than that in Figure 13. The new contact chamber showed the opposite trend of when it was tested at 0.6 mL/s. It caused an almost constant increase in headloss throughout the experiment time. In terms of the total difference between the beginning and end of the experiment with the old contact chamber, the new contact chamber held a slower increase in headloss. This is still and advantage for the latter but it shows that the ratio of clay to contact chamber surface area may need to be increased for higher flow rates. Note that the contact chamber was designed for a turbidity of 50NTU and flow rate has not effect on the ratio. However, at a lower flow rate (0.6 mL/s) the residence time does increase, perhaps providing more opportunities for attachment of the coagulant to the clay .

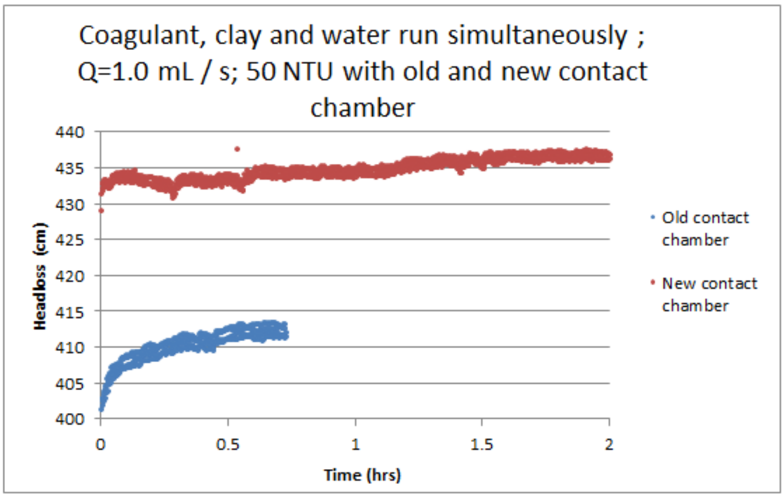

Figure 14: Again, there was a clear increase in headloss when using the old contact chamber. In contrast to Figure 13 the new contact chamber caused an increase and then steady value of headloss . The difference in run times is very large, and in the case of the red series, it was decided upon because of the longer residence time of the contact chamber (about 27 minutes versus 1.06 minutes for the old contact chamber).

The experiments with 5 NTU turbidity water were only done with the new contact chamber . As previously stated it was designed for 50 NTU water. Thus, lower turbidities would cause the surface area ratio to decrease significantly and would result in a less efficient contact chamber . Figure 15 shows the red series, representing a 1.0 mL/s flow rate, and the constant increase in headloss. The rate of increase is also higher than that seen for the same flow rate in Figure 14.The lower flow rate in Figure 15 showed more variability in headloss but an overall lower increase. Again, the residence time might have been a factor causing the 0.6 mL/s flow rate to be more effective. It is consistent with the decrease in headloss seen in the 50 NTU experiment in Figure 13

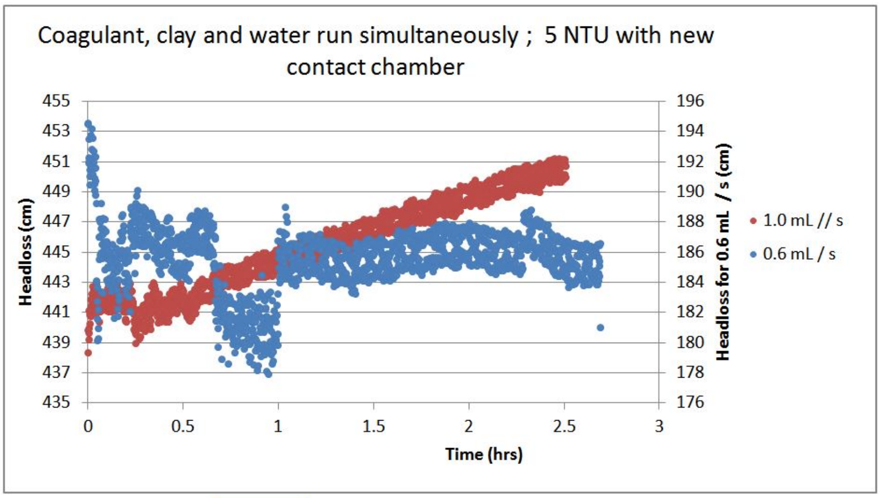

Figure 15: The plot shows how the higher flow rate, in red, resulted in a constant increase of headloss for the whole 2.5 hours. The 0.6 mL/s flow rate showed more variability and had a lower average headloss value. The lower flow rate helped maintain lower overall values of headloss and is consistent with the comparison between Figures 13 and 14.

The purpose of the coiled flocculator was to design for a known headloss and residence time, of 50 cm and 1 minute respectively. These parameters more closely reflect those of realistic water treatment plants. However, the main focus was the contact chamber. The experiments with the coiled flocculator were thus based on seeing whether it would exhibit the same increase in headloss with accumulation of free coagulant. With that information, subsequent tests with the team's new contact chamber could be tested with both the microbore and coiled flocculators. However the results were inconclusive. Figure 16 displays the results of coagulant, clay and water run to achieve a turbidity of 5 NTU at 0.6 and 1.0 mL / s flow rates. Compared to the microbore flocculator in Figure 11, it is clear that the increase in headloss is insignificant for the 0.6 mL /s flow rate and for a 1.0 mL /s flow rate it increases at a much slower rate. Thus, the results show that there is some measure of coagulant attachment in the coiled flocculator, but it did not enhance the team's understanding of the relationship between headloss and free coagulant. The coiled flocculator was thus put to the side to complete experiments that focused on analysing the contact chamber.

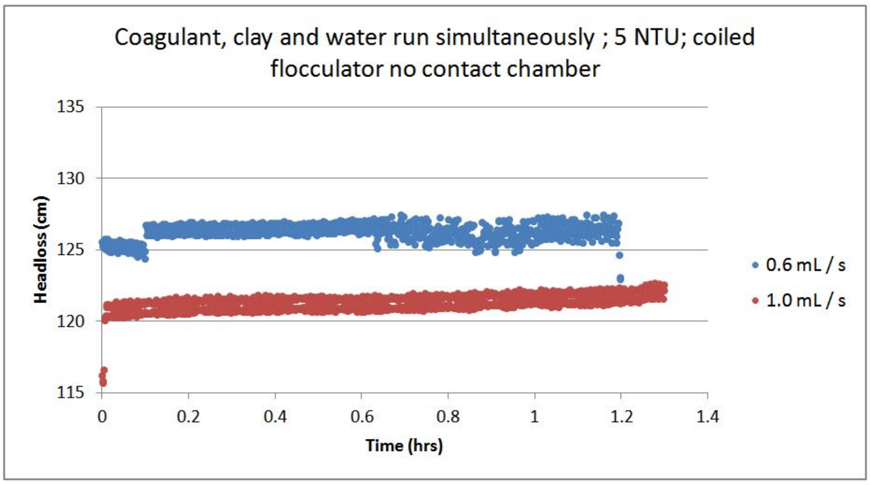

Figure 16: The coiled flocculator design was included in only low turbidity experiments to determine whether coagulant attachment was as noticeable as in the previous microbore flocculator. The results show that the increase in headloss due to probable coagulant attachment is very gradual for the 1.0 mL/s flow rate and even more insignificant for a 0.6 mL/s flow rate.

The new contact chamber was previously compared to that used by the Fall 2016 team. However, Table 1 and Table 2 summarize the experiments at all flow rates and turbidities to compare the raw effect of the new contact chamber to when the system had no contact chamber at all. In all combinations, the new contact chamber yielded lower headloss per hour values than when no contact chamber was present. The largest differences are seen for the 1.0 mL/s flow rate. If the microbore flocculator is a true measure of free coagulant as supported by the results in this reports, then these changes in headloss rates are the start to determining a contact chamber design that can mitigate coagulant loss to the walls of the flocculator. However, there are many factors that have to be analyzed further and tested with more precision. For example, the contact chamber was designed to increase the surface area ratio of clay to wall surface area but there is still a possibility that the free coagulant is sticking to the contact chamber walls instead of in the flocculator.

Headloss change with no contact chamber		
Q (mL / s)	NTU	Headloss (cm / hr)
0.6	5	7.21
0.6	50	5.18
1.0	5	17.79
1.0	50	13.10

Table 1: This table summarizes the headloss rates for all experiments conducted with the microbore flocculator design from the Fall 2016 team with no contact chamber. The values for the 1.0 mL/s flow rate are higher for both turbidities, due to the greater magnitude of water flow through the small diameter flocculator.

Headloss change with new contact chamber		
Q (mL / s)	NTU	Headloss (cm / hr)
0.6	5	0.83
0.6	50	-4.07
1.0	5	4.48
1.0	50	1.35

Table 2: This table summarizes the headloss rates for all experiments conducted with the microbore flocculator design from the Fall 2016 team and the current team's design for a contact chamber. Again, the values for the 1.0 mL / s flow rate are larger. The difference for each combination of flow rate and turbidity between this table and 1 suggest the contact chamber has a mitigating effect on free coagulant in the flocculator.

Conclusions

The preliminary results reflected what was expected based on the experiments of (Krishnamoorthysujatha et al., 2016). The main observation of similitude is an increase in headloss when coagulant is mixed with the influent water, and an apparent steady value of headloss in Figure 9 when water and coagulant are pushed through the system at a high flow rate. The team concluded that the tube flocculator can be a detector for free coagulant because the general amount of coagulant attached to the wall can be determined by measuring the headloss.

Another conclusion was the fact that the clay does not have a significant impact on coagulant deposition for low turbidity systems. The headloss still increased with the addition of clay. Knowing that the coagulant will attach to any surface available, it is far less likely to attach to clay particles if the surface area of clay particles is significantly lower than the surface area of the flocculator. As a result, for systems that have small amounts of clay, there is little chance for the coagulant to attach to the clay particles in the water. This problem can be solved by adding a contact chamber, which gives a chance for the clay and coagulant to mix and attach to each other before entering the flocculator, potentially decreasing the loss of coagulant to the walls.

The results of the contact chamber tests indeed showed that there is a noticeable decrease in the rate of headloss increase when using a contact chamber with a more favorable surface area ratio (Figure 14). The effect was more pronounced for higher turbidity systems. In general, a larger diameter contact chamber, when compared to that of the flocculator, yields a higher ratio of clay surface area to chamber surface area. The surface area ratio takes into account the influent turbidity, so that with lower turbidity systems a larger diameter contact chamber will be needed to maintain a favorable ratio. This suggests that when designing a contact chamber, it would be most beneficial to design for the lowest turbidity that may occur during a year.

Future Work

One of the most important results the team concluded this semester was the fact that with an increased ratio of total clay surface area to the surface area of the contact chamber, the team can reduce the amount of free coagulant attaching to the walls of the flocculator, and thus potentially increase coagulant efficiency. However, given that this might be because some coagulant has attached to the walls of the contact chamber, the future team should focus on finding out whether or not this is a problem. One method could be to test the system with and without a contact chamber while monitoring sedimentation and turbidity of effluent water. This could help the team see whether enough coagulant is attaching to the walls for the treatment process to no longer work as well.

In order to optimize the efficiency of the contact chamber, next semester's team should also consider the flow of the water in the contact chamber. A design so the inlet jet diameter reaches the chamber walls only at the end of the contact chamber could minimize coagulant attachment to the walls of the contact chamber.

References

Dentel, S. K. (1991). Coagulant control in water treatment. *Critical Reviews in Environmental Control*, 21(1):41–135.

Krishnamoorthysujatha, M., Moraes, J., and Escanciano, J. (2016). Rapid mix contact chamber Fall 2016.

Letterman, R. D., Quon, J. E., and Gemmell, R. S. (1973). Influence of Rapid-Mix Parameters on Flocculation. *Journal (American Water Works Association)*, 65(11):716–722.

Tzoupanos (2008). Coagulation–flocculation processes in water/wastewater treatment: the application of new generation of chemical reagents (PDF Download Available). *ResearchGate*.

Vrale, L. and Jorden, R. M. (1971). RAPID MIXING IN WATER TREATMENT. *Journal (American Water Works Association)*, 63(1):52–58.

Zu, A., Whiting, J., and Athavale, A. (2016). Rapid mix contact chamber Spring2016.

Semester Schedule

Task Map

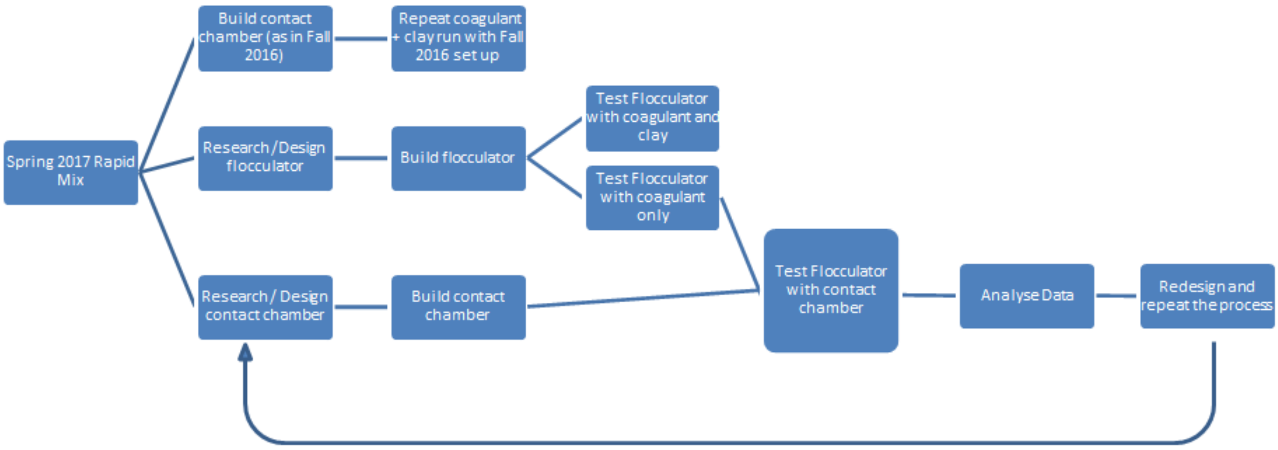

Figure 17: Task Map

Task List

1. Build contact chamber (as in Fall 2016): (2/21-2/23) - Philip Akpan. Try to build chamber with same dimensions as Fall 2016 to replicate experiment they did with coagulant + clay .

2. Repeat coagulant + clay run with Fall 2016 set up (2/21-2/23) - Karin Teuffer. Run experiment with Fall 2016 design of flocculator and contact chamber

3. Research / Design the flocculator (2/21)- Karin Teuffer. Research and decide whether to use a coiled tube as a flocculator or to follow Fall 2016's straight tube design.
(2/12-2/14). Design the flocculator with a headloss of 50cm and a residence time of around 1 minute.

4. Research /Design the contact chamber (2/21-2/23) -Philip Akpan. Research and decide whether to use a cylindrical shape. Last semester's contact chamber was designed to have a slightly longer residence time than the flocculator so that the coagulant and clay have time to come into contact.
(2/21-2/23). Design the contact chamber .

5. Build the flocculator (2/23- 2/26)- Grace Zhang. Build a flocculator that produces flocs .

6. Build the contact chamber (2/23- 2/26) - Philip Akpan. Fabricate the contact chamber .

7. Test flocculator (2/27-3/1). - Grace Zhang. Test the flocculator and compare experimental head loss to design head loss without coagulant (just water). Determine limiting (max) flow rate at which coagulant does attach to walls of flocculator . Then test at this flow rate with coagulant but without the contact chamber . Measure head loss through flocculator using ProCoDA software. *first research report due 3/3

8. Test flocculator with contact chamber (3/5-3/9) - Karin Teuffer. Test the flocculator with the contact chamber at different flow rates and with different initial turbidities . Measure head loss through flocculator using ProCoDA software. Possibly measure head loss change through contact chamber as well.

9. Analyze Data (3/12-3/21) - Grace Zhang . Attempt to answer question of whether contact chamber helps distribute coagulant so that more mixing and contact occurs between clay and coagulant or does it simply cause more coagulant to attach to the walls of the chamber before reaching the flocculator.

10. Redesign (3/23-3/30) - Person in charge TBD. Do we need to redesign any part of the tested system? Why? Possibilities include new ideas for testing loss of coagulant through either flocculator or contact chamber .

Report Proofreader : Karin

Manual

Materials

The dimensions of the most important materials for replication are included in the following section:

- Peristaltic pumps : One used for each of the raw water (max 600 RPM), clay (max 100 RPM) and coagulant (max 100 RPM) flow controls.
- Size 16 pump tubing (3 mm diameter): Used for the water pump
- Yellow-blue tubing (1.52 mm diameter): Used for the clay pump and the coagulant pump
- Nylon tight-seal barbed tube fitting (3/32" (2.38 mm) Tube ID * 1/8 Male Pipe Size): Used for connecting all pump tubing to micro tubing and hard tubing, as necessary .
- Hard tubing (6.35 mm in diameter): Used to connect pump tubing to raw water supply and influent point of contact chamber , as well waste water connection.
- Micro-tubing (0.38mm in diameter): Connected to the yellow-blue tubing in order to pump clay and coagulant out of the container; it also connects the coagulant pump to the contact chamber.
- Push-to-connect fittings (3.18 mm in diameter): Used to mix the clay and water before entering the turbidity meter, connect the the water source to the water pump, and connect the influent water and clay to the turbidity meter, contact chamber, flocculator, and waste.
- PVC pipe (76 mm in diameter, 0.203 m long) : The main body of the contact chamber
- Standard-Wall PVC Pipe Fitting (76 mm in diameter) : The caps used for either end of the contact chamber .

Experimental Methods

The team used the equations and MathCAD files created by the Fall 2016 team Krishnamoorthysujatha et al. (2016) to validate and later, modify the experimental set up.

1. Run the experiment without the contact chamber and test the effect of coagulant on the flocculator.
   (a) Pump the tap water through the water pump controlled manually and pump the coagulant through the coagulant pump.
   (b) Before each new experiment, increase the flow rate and let water flush through the flocculator so that the coagulant attached to the walls from the previous experiment can be washed off.
   (c) Put the coagulant stock on a weight so the team can measure the mass of the coagulant that is flowing through the system. Because the tubing the team uses for the coagulant is very thin, this is also an useful way for us to make sure the coagulant is actually flowing through the system.
   (d) Set up the ProCoDA so that only the coagulant pump will turn on as the team start the experiment. Adjust the set points to run the experiment with designated flow rate and rpm.
2. Add the contact chamber to the apparatus and run the experiment with same flow rate to test the effect of contact chamber
   (a) Make sure the contact chamber is full before starting to record the results. Which means before running experiments with a new contact chamber, run water through the system for a time longer than the designed residence time of the contact chamber.
   (b) When running an experiment with a contact chamber with longer residence time and switching the concentration of solutions between each experiment, make sure to run water through the system for a longer amount of time to minimize the effect of the solutions in the contact chamber left by the previous experiment.

3. Run the experiment with clay solution
   (a) For experiment with clay, mix the clay solution with the clay mixer before the experiment starts.
   (b) Change the ProCoDA file so that the clay is mixed for a certain amount of time before the experiment starts to make sure the clay particle is evenly spread in the solution.

Cleaning Procedure

(a) Make sure the state in ProCoDA is "OFF" and exit ProCoDA
(b) Turn off the water pump manually and shut off the water source and the drain.
(c) Make sure all the data are collected correctly and are in the right folder.
(d) Write the tasks accomplished in the log book and note any problems that need to be addressed.

Experimental Checklist

A list of things that you need to check before running an experiment.

- Check if all the equipments are correctly connected to the power, the computer, the ProCoDA box and all the connections between different parts of the apparatus are water-tight.
- Check if the ProCoDA states and set points are set up correctly. Put ProCoDA on automation if you want the experiment to stop after a certain time.
- Check if both the water source and the drain are connected and turned on. Because the water is controlled manually through the water pump, make sure the pump rate is set up correctly for the pump and shut off the pump after experiment is over.
- Check if the pressure sensor is connected correctly. No water should flow through the tube connected to the pressure sensor after the drain is opened.
- If the team is running an experiment with the clay, check if the clay-mixer is working correctly and pre-mix the clay for the set pre-mixing time.
- Check if the coagulant is being pumped through the coagulant pump by measuring the weight of the coagulant tank.
- Check if the turbidity measured by turbidity meter is close to the designed turbidity of the system. Given that the water evaporates at a slow rate under room temperature and may cause an increase in the turbidity, add water if necessary. If the turbidity is too low, check if the clay pump is working correctly.

Sample parameters

The parameters for running the experiments for a 0.6 mL/s flow rate were:

- Raw water pump : 42 RPM
- Total plant flow rate (approximated with raw water flow rate) : 0.6 m L/ s
- Clay water solution pump : 20 RPM
- Clay water solution flow rate : 0.05 mL /s
- Clay water solution concentration : 5 NTU or 0.468 g clay per 4 L of water
- Coagulant pump : 8 RPM
- Coagulant stock concentration (in 1 L bottle):
- Coagulant flow rate : 0.021 mL / s

ProCoDA Method File

States

- OFF - Resting state of ProCoDA. All sensors, relays, and pumps are turned off.
- ON
- Run clay mixer - Run the clay mixer for pre-mixing before the experiment starts.
  - In this state, only the clay mixer is turned on. It will run for the "pre-mixing time", which is defined as a set point, and then go to the next state, which is defined as "Run Experiment"
- Run experiment - Start the experiment by turning on the coagulant and clay pump
  - The clay mixer is turned off as the experiment starts. The clay pump might not be turned on based on which step of the experiment the team is performing.
  - The water pump is turned on manually because we can only connect two pumps to ProCoDA. So this state in ProCoDA does not control the water pump.

Set Points

- Clay Flow Rate - The flow rate for the clay solution, calculated from the MathCAD file (The team used 0.05mL/s for this experiment)
- Coagulant Flow Rate - The flow rate for the coagulant solution calculated from the MathCAD file (The team used 0.021mL/s for this experiment)
- Tap Water Flow Rate - The flow rate for the tab water calculated from the MathCAD file. (The team used 0.547mL/s for this experiment)
- mL per rev yb - 0.149 mL/rev
- Coagulant Pump Speed - Settings for the coagulant pump
  - Selected set points: "Coagulant flow rate" and "mL per rev yb".
  - VI file selected: "pump control (mL per s, mL per rev).vi"
- Clay Pump Speed - Settings for the clay pump
  - Selected set points: "Clay flow rate" and :mL per rev yb:
  - VI file selected: "pump control (mL per s, mL per rev).vi"
- Unit ID - 1 (indicates turbidity meter identification for program)
- Turbidity Meter - Record the turbidity data.
  - Selected set points: "UnitID"
  - VI file selected: "HF turbidity meter(com1).vi"
- Pre-Mixing Time - The time that the clay mixer is turned on before the experiment. (The team used 20s for this experiment)
- Experiment Time - The time that the actual experiment will take place. It can be changed to any number.

Relevant Equations

Surface Area Equations

$$C_{clay} = 50NTU * 1.7\frac{\frac{mg}{L}}{NTU} = 85\frac{mg}{L}. \tag{9}$$

$$V_{tube} = \pi\frac{D_{tube}}{4}^2 L = 0.021m^3. \tag{10}$$

$$TotalMass_{clay} = C_{clay}V_{tube} = 5.823 * 10^{-6}kg. \tag{11}$$

$$TotalV_{clay} = \frac{TotalMass_{clay}}{\rho_{clay}} = 2.377 * 10^{-9}m^3. \tag{12}$$

$$N_{clay} = \frac{V_{clay}}{\frac{4}{3}\pi\frac{D_{clay}}{8}^3} = 7.093 * 10^7. \tag{13}$$

$$SA_{clay} = 4\pi\frac{D_{clay}}{4}^2 = 5.027 * 10^{-11}m^2. \tag{14}$$

$$SA_{contactchamber} = \pi D_{tube}L = 0.049m^2. \tag{15}$$

$$Total_{SAClay} = N_{clay}SA_{clay} = 3.57 * 110^{-3}m^2. \tag{16}$$

Note: C refers to concentration, D to diameter, V to volume, N to number of particles, and SA to surface area.

Special Components

Not Applicable