Rapid Mix Contact Chamber, Spring 2016

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Abstract

The Rapid Mix Contact Chamber team worked to build a contact chamber that allowed for the rapid mixing of raw water and coagulant, improving upon the existing Rapid Mix Tube by providing a larger volume for mixing to take place. The goal was to determine the shape of the contact chamber that would result in the least coagulant loss and to determine the residence time needed to maximize mixing but minimize coagulant loss. pC* was used to measure coagulant loss and pigging was used to clean the flocculator in between trials. Results showed that contact chambers of any kind improved the efficiency of flocculation and reduced loss of coagulant to the walls of the apparatus. Increasing residence time also increased the contact chamber's efficiency.

Introduction

The Rapid Mix Contact Chamber team was created to address the problem of loss of coagulant in the rapid mix tube and flocculator of the AguaClara plants. A high amount of coagulant added was attaching to the walls of the current tube instead of sticking onto particulates. For the team's model of the plant, only 1.6 percent of coagulant used actually attached to clay particles (Weber-Shirk, 2015). Although the coagulant build-up is not hindering the water's ability to flow through the plant and flocculation is still possible, the plant would be more efficient if the loss of coagulant was minimized. The biggest impact of loss of coagulant is wasting money. The team's goal was to design and construct a contact chamber to add to the rapid mix process in order to minimize the loss of coagulant. The contact chamber created a mixing space with a larger volume so the coagulant had a higher chance of sticking on a particulate than it had of sticking to the walls. The tubing in the team's flocculator represented the walls and baffles of the flocculator in the AguaClara plants, so the team's apparatus imitated the actual AguaClara plants. In other words, the coagulant on the walls of the tubing in the model is the equivalent of coagulant on the walls and baffles in the plant. In the future, the Rapid Mix Contact Chambers could be used to decrease coagulant doses needed to properly clean the water, and as a result, villages that use AguaClara plants could lower costs. The contact chambers would also result in cleaner water because the coagulant would be used to create flocs and remove particulates instead of being lost to the walls.

Literature Review

Rapid mix contact chambers are used in water treatment facilities across the United States. The Robert A. Harris Water Filtration plant in Eden, North Carolina, for example, uses multiple rapid mix chambers. The coagulant and other chemicals are added prior to the contact chambers and the total residence time in the chambers is approximately 1.6 minutes Eden NC (2011). In this plant, a five horsepower mixer creates the high turbulence needed for effective mixing.

Rapid mix is a high-intensity mixing step used before flocculation to disperse the coagulant and to initiate the particle aggregation process. There are two steps in a rapid mix process:

First, macro mixing. In this step, the size of large scale eddies depend on the dimensions of the reactor. Devices are used to generate large eddies then make the flow expansion with dimensions similar to the dimension of the reactor.

Second, micro mixing. In this step, small scale eddies mix down to the Kolmogorov length scale. Large eddies generate energetic tiny eddies so that turbulence can mix at the length scale of particle separation. The Kolmogorov length scale is the smallest length scale in turbulent flow. At the Kolmogorov length scale, viscosity dominates and the turbulent kinetic energy is dissipated into heat. The length scale is defined by:

$$L = \left(\frac{v^3}{\epsilon}\right)^{\frac{1}{4}}$$

where the variables are as follows:
L — the Kolmogorov length scale, m
ν — the kinematic viscosity, m^2/s
ϵ — the energy dissipation rate, mW/kg

In conventional rapid mix, people use a mechanized method to generate turbulent flow. However, this method uses a great electricity load and costs more than 60,000 dollars annually for a 100 L/s plant. Consequently, AguaClara figured out a hydraulic method to reduce the cost and improve the efficiency.

The principle of rapid mix is to convert kinetic energy into thermal energy, which means concentrated head loss is needed. So AguaClara made use of the changes in flow geometry to produce flow expansion. In this way, the required energy dissipation rate to mix particles and coagulant is achieved. Weber-Shirk (2015).

A common use of contact chambers in water treatment plants is to add ozone for disinfection. The residence time, θ, for these contact chambers are between 13 and 15 minutes. The volume is calculated by:

$$V = Q * \theta \tag{1}$$

These contact chambers use baffles to produce turbulence. The contact chambers are rectangular in shape (Semerci, 2012).

Previous Work

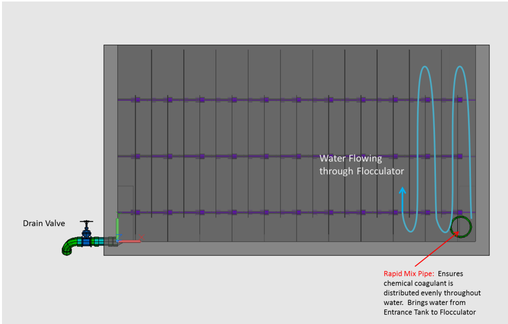

Figure 1: This figure displays the Rapid Mix Pipe and Flocculator of the AguaClara plants. Water enters through the Rapid Mix Pipe on the right-hand side and exits the system through the flocculator on the left-hand side.

A rapid mix tube has been implemented in AguaClara plants. The tube, as shown in figure 1, which connects the entrance tank and the flocculation tank, serves to provide an area in which the raw water can mix with the coagulant. The goal of the Rapid Mix Contact Chamber subteam is to address the high coagulant loss to the sides of the rapid mix tube by designing a rapid mix chamber of greater volume. The team researched/ the effects of the shape of the rapid mix contact chamber and the residence time in the chamber to determine if having a rapid mix contact chamber instead of a rapid mix pipe will lead to less coagulant loss. In the Fall 2009 semester, a subteam researched the best design for a rapid mix pipe.

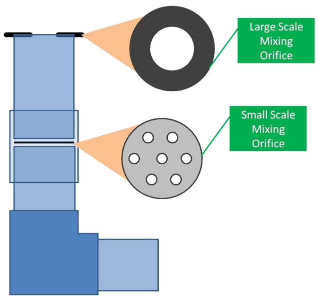

Figure 2: This figure displays the designs of small and large scale mixing in the Rapid Mix Pipe.

The team concluded that the schematic design, shown above in Figure 2, is the best geometry for small and large scale mixing. This design was chosen to create proper eddies and mixing. The circular holes and even spacing of the holes result in the small-scale mixing with an even coating of the coagulant on particles. The small-scale mixing determines the head loss or energy dissipation achieved for the plantSwetland (2012).

Methods and Discussion

The team used the method of mass balance to determine the amount of coagulant lost to the walls of the flocculator in each trial. The mass of the flocculator was measured before and after the experiment to see if an increase in mass could be observed. In later trials, the mass was recorded continuously during an experiment to give more insightful data about the increase in mass. The team then used pigging to remove the coagulant from the walls of the flocculator tube. In this step, a sponge was placed at the inlet of the flocculator tube and water was run through the system. The sponge collected the coagulant from the walls of the flocculator. Finally, the team blew air through the system in order to remove the water from the pigging step. The air was blown from a condensed air pipe through a tube that was connected to the flocculator. The team then measured the mass of the flocculator again, to see if the flocculator returned to the original dry mass.

Obtaining consistent mass balance results was difficult to achieve due to tension forces in the tubing of the apparatus, so the team moved to measuring coagulant loss through the performance of a tube settler. The pC* was recorded throughout a test and the team correlated better performance of the tube settler (a higher pC*) to a decrease in coagulant loss. A lower coagulant loss should increase flocculation and sedimentation efficiency, and therefore should increase the performance of the apparatus. Since the team observed a higher pC* with a contact chamber in the apparatus than without it, the team concluded that the apparatus was more efficient with a contact chamber. The team also concluded that less coagulant was being lost to the walls when a contact chamber was present in the apparatus.

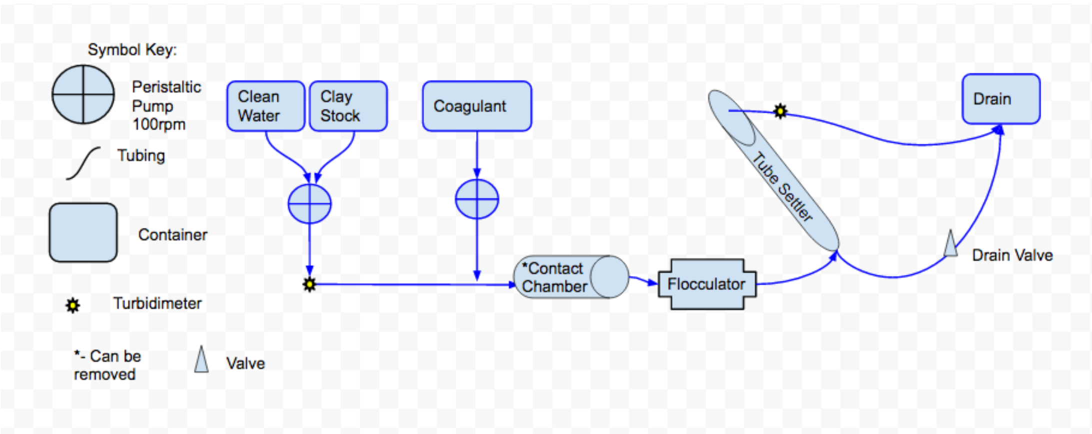

Figure 3: Schematic of Final Testing Apparatus. This is meant to mimic the rapid mix pipe and flocculator of the AguaClara plant. The contact chamber is detachable and new ones can be attached for different tests.

Standard Operating Procedure:

Starting a Test:

1. Ensure tap and waste water valves are closed
2. Remove clay stock tubing from pump and plug the connection with tap water to ensure no clean water flows back into clay stock
3. Open tap and waste water valves
4. Turn on both pumps
5. Switch the clay/water pump into int mode
6. Set the pump speed to 50 RPM and turn the pump on
7. Allow clean water to fill the entire apparatus, then stop the pump
8. Set pump to mA mode
9. Close tap and waste water valves
10. Remove plug and reattach clay stock tubing
11. Open tap and waste water valves
12. Plug in stirrer
13. Turn on turbidity meter
14. Begin test with ProCoDA, when influent NTU reaches 5, send message "begin" to data sheet

After a Test:

1. Turn Off Pumps
2. Unplug Stirrer
3. Close tap and waste water valves
4. Turn off Turbidity Meter

Clean-up:

1. Ensure tap and waste water valves are closed
2. Detach drain pipe from apparatus
3. Open valve on drain pipe
4. Detach tubing from top of tube settler and allow water to drain
5. Detach flocculator from apparatus and allow to drain
6. If contact chamber is being tested, detach contact chamber and drain
7. Reattach tubing to tube settler, reattach drainage pipe and close drain pip valve
8. Use pigging to clean the flocculator and rinse out contact chamber
9. Reattach flocculator after cleaning. If testing contact chamber again, also reattach this after cleaning

The team's final schematic is shown in Figure 3 below:

First Iteration

The goal of the first iteration of experiments was to determine the feasibility of measuring coagulant loss through mass balance and to define parameters for how the team's future experiments would be run. The first task was to determine whether the mass balance method of data collection would work for the apparatus. Experiments were run until a noticeable mass difference of the flocculator could be detected before and after a run. The mass difference was attributed to the coagulant build-up on the flocculator walls, though the team could not visually detect such a build-up. The second half of this experiment was to make sure the flocculator cleaning method was consistent in fully cleaning the tube. The team used pigging, a method in which a small sponge was placed at the inlet of a tube and water was used to push the sponge through the tube. As the sponge traveled through the tube, it collected the solid materials stuck to the sides of the tube, thus removing the solids from the tube. After pigging, the mass of the flocculator was measured again to ensure it was back to the initial "clean" weight.

Experimental Apparatus 1

The design for the flocculator was based on research by the StaRS Filter Theory team(Chu et al., 2016). The flocculator was 0.3175 cm inner diameter tubing and 3 meters long, with a radius of curvature 0.058 meters and a residence time of 12.075 seconds. The team designed their own flocculator based on that of the StaRS Filter Theory team because the design target of $G\theta$, the velocity gradient multiplied by the residence time, was set at 5000, and due to the parameter of the flocculator, the residence time was 24.15 s. The difference in residence time between the teams' flocculators was due to the team's flow rate being double that of the StaRS team. The team used this design for the flocculator because the function of the StaRS Filter Theory team's flocculator was similar to the intended function of the team's flocculator. The flow rate through the overall apparatus was 1.967 mL/s. The schematic of the first apparatus can be seen in Figure 4 and a labeled photograph in Figure 5 below.

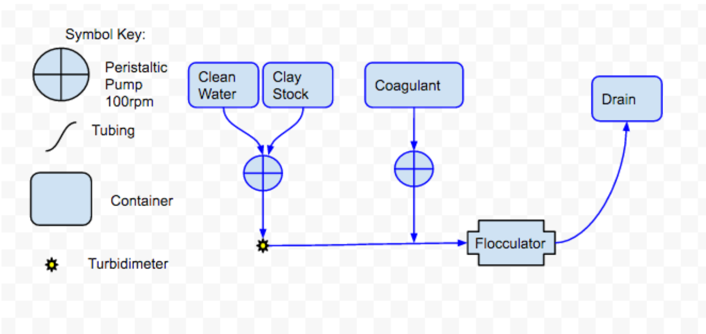

Figure 4: Schematic of Initial Testing Apparatus. This is meant to mimic the rapid mix pipe and flocculator of the AguaClara plant. The flocculator is detachable and is weighed before and after testing to determine weight of coagulant build-up.

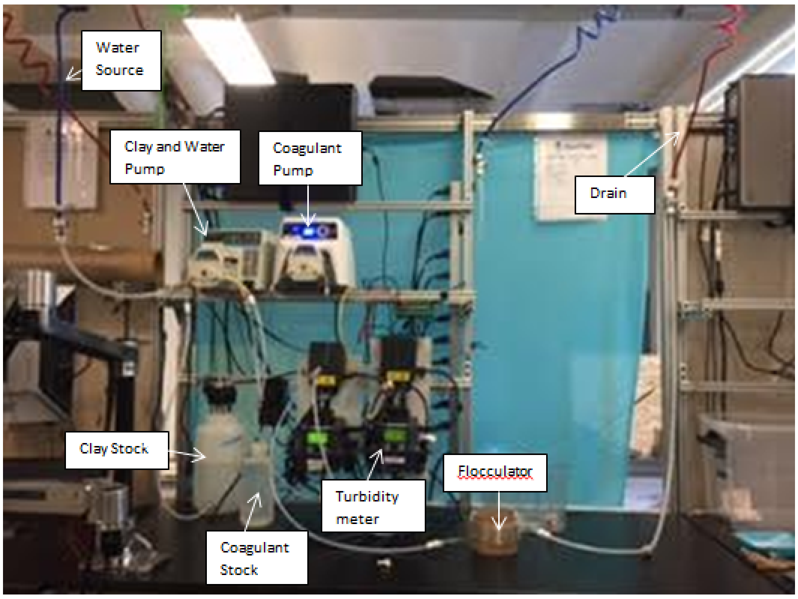

Figure 5: Initial Testing Apparatus Image. Clay and coagulant stocks are the plastic bottles in the lower left corner. Fresh water flows in the blue tube. The pumps are in the upper left hand corner of the photo, the water then flows into the turbidity meters on the bottom left hand side and then through the flocculator in the middle then out the red tube to the drain.

The team used an air pump to blow air through the flocculator after an experiment to dry the tube, so that the post-experiment mass could be recorded. For pigging, the team used the faucet, an adapter, and small sponge. The sponge was 0.37 cm in diameter. The faucet and the faucet adapter created pressure so that the sponge could be forced through the flocculator for the cleaning process.

Procedure 1

First, the team weighed the initial mass of the flocculator (without the connector). Then the team ran an experiment for 30 minutes and weighed the flocculator again. By measuring the mass of the flocculator before and after the experiment was run, the team was able to determine the mass of coagulant lost to the flocculator walls. For the first two runs, the team used a coagulant concentration of 1 mg/L and an influent turbidity of 5 NTU. For the third run, the coagulant dose was 2 mg/L.

Results and Analysis 1

In the first test of the apparatus, the team was not able to observe a mass difference of the flocculator before and after the experiment was run. Because the team did not detect a change in mass of the flocculator for these initial parameters, the team tested the apparatus with an increased coagulant concentration of 2 mg/L. The coagulant supply was accidentally cut off at some point during the first experiment which is a possible reason for why there was no detectable change in mass. In the second iteration of this experiment, a detectable increase in mass of 1 g was recorded. In the third iteration with a more accurate scale (Precision of 0.01 g instead of precision of 1 g), there was only a 0.06 g difference in mass. Flocs were not observed in any of these tests.

Table 1: Mass Balance for Initial Apparatus Testing

Initial Mass	Mass after Trial	Mass after Cleaning
141 g	142 g	141 g
140.98 g	141.04 g	N/A

Because the first test was only 30 minutes, there was no detectable change in mass, so the results are not included in the table above. The results from these two trials were not consistent with each other and showed that more testing is needed to demonstrate that coagulant is lost to the flocculator walls. The first trial shown in the table was run with 1 mg/L coagulant dosage and the second was run with 2 mg/L dosage. Therefore, the team expected an even higher increase in mass during the second trial than the first. The results did not follow the team's hypothesis. The results also demonstrated that the team should use the more accurate scale for better accuracy in determining the mass of the flocculator before and after testing. In addition, longer tests or higher coagulant concentrations could better show the coagulant loss. The team observed no flocs because the energy dissipation rate was so high that flocs that were made broke apart.

Second Iteration

During this iteration, the team ran longer experiments to more accurately capture what happens in an AguaClara plant. Four 24 hour experiments were conducted and the mass of the flocculator was measured continuously throughout the experiments as opposed to before and after experimental trials.

Experimental Apparatus 2

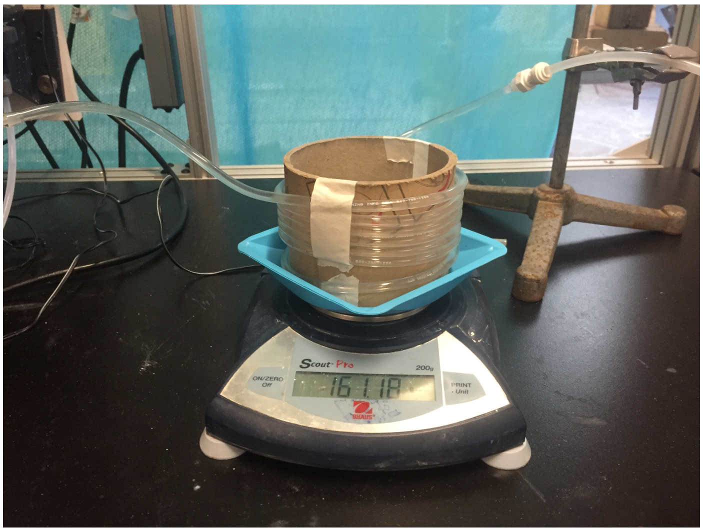

Figure 6: This photo shows the current setup of the flocculator with the mass balance. This is the setup that was used to continuously record the mass of the flocculator throughout the experiment. The change in mass represents the coagulant and clay sticking to the walls.

As can be seen in Figure 6, there were clamps holding the tubes of the flocculator in place during a test. The clamps were necessary for continuous testing because shaking of the table affected the balance's results.

ProCoDA Methods 2

In the second iteration, the team used ProCoDA to control the pumps for the tests. The team used ProCoDA to run longer experiments without having to watch over the apparatus for the entire 24-hour period. The team also automated the stirrer with ProCoDA so that it would run only during the experiments.

- States:
  - Run: Begins experiments. On - clay pump, coagulant pump and stirrer.
  - Off: Off - clay pump, coagulant pump and stirrer.
- Set points
  - On: Turns pumps or stirrer on.
  - Off: Turns pumps or stirrer off.
  - Time: Controls run time of the experiments.
- Variables:
  - Pump Speed: This variable is controlled by PID code which makes the pumps produce the desired flow rate.

Procedure 2

In the second iteration, the tests were run for 24 hours instead of only thirty minutes. Also the method of recording data changed. The flocculator was placed on a mass balance (0.01 g precision) as shown above, and the mass of the flocculator during the experiment was manually recorded throughout the test. Pigging was still used as the method to clean the flocculator between tests. The flow rate was halved to 0.984 mL/s to decrease the energy dissipation rate which was previously too high to create flocs. The cause of the absence of flocs was discovered when the team remodeled the flocculator and checked the energy dissipation rate.

Results and Analysis 2

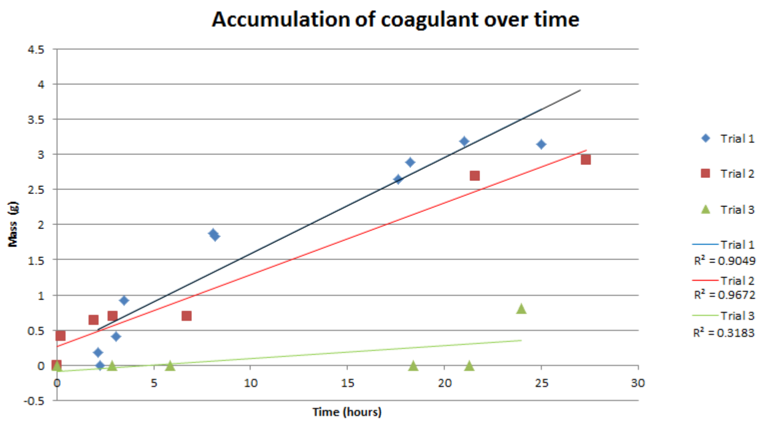

Figure 7: In these experiments the change in mass in the flocculator during a twenty-four hour test was recorded. The influent was a clay water solution with a turbidity of 5 NTU. The mass was zeroed at the beginning of the experiment so negative mass means a decline in mass.

In the first 24 hour experiment, shown in Figure 7, there was a decrease of four grams at the beginning of the experiment and then a steady mass gain throughout the rest of the test.

The initial decrease could have been because of a team member knocking the table or the stirrer shaking the table. A slight movement in the position of the flocculator could have caused a drastic change in mass reading. The steady gain of mass after the loss represented coagulant on walls of the flocculator.

In the next iteration of this test, the results showed the same steady increase in mass, accumulating to 3 grams without the initial decrease of the first test. This test, in Figure 7 , showed the trend that was expected: a linear increase in mass over time. However, the team calculated that only 0.491 grams of coagulant and 0.722 grams of clay were added to the system. The sum of these numbers was less than the increase in mass of the flocculator. The team believed the additional mass reading came from the stirrer that was shaking the table while stirring the clay solution. This meant that the mass balance did not give correct readings. To resolve this issue, the stirrer was moved to a neighboring table so that its shaking would no longer affect the results of the experiments.

The last two iterations of the experiment yielded varied results. The team believed that such mixed results were due to issues with the mass balance. The first of these two experiments resulted in a 0.81 gram increase of the flocculator, which was reasonable, as this value was less than the total mass added to the system.

In the second of these trials, the scale did not give a steady reading, and the mass either continuously decreased or increased throughout the experiment. Therefore the data was inconclusive. These tests showed a promising measurement technique, but the equipment and process need to be perfected before they can be used to determine the effects of a contact chamber on the rapid mix process. Once the accuracy of the equipment and process of measurement are improved, comparisons can be made between the loss of coagulant in the presence of a contact chamber and the loss of coagulant when no contact chamber is used.

Third Iteration

For the third iteration, the team attached a USB connector to a scale from which ProCoDA read in data. By using the USB connector, the team was able to obtain regular mass readings of the flocculator.

Experimental Apparatus 3

In this iteration, the team used a USB connector that attached to the balance. This connector allowed the team to continuously record the mass of the flocculator over the 24 hour experiments.

For the last test, the calibration test, the team decided to use the original flocculator design again. The larger tubing size of the modified flocculator created tension in the flocculator, which could have lead to less accurate mass readings. For the calibration test, a shorter version of the original flocculator was implemented. Its specifications were: 0.3175 cm inner diameter tubing , 2.31 meters long, with a radius of curvature 0.058 meters and a residence time of 18.596 seconds.

ProCoDA Methods 3

The team added the mass variable to the ProCoDA so that data was recorded continuously during a test.

- Variables:
  - Mass: The variable recorded the mass of the flocculator every 60 seconds during a test.

Procedure 3

For this iteration, the team performed two more 24 hour experiments as well as a calibration test. The team used ProCoDA to measure the mass of the flocculator every 60 seconds throughout the experiments. All other parameters, including coagulant dose and clay concentrations, were held constant. The experiments in this iteration measured the change in mass of the flocculator over time like the previous experiments did, except the mass was recorded continuously. The calibration test was performed to determine the accuracy of the balance. In this test, the mass of the balance was recorded over a 24 hour period; however, there was no water running through the apparatus. However, before the experiment water was put in the flocculator to give it a comparable weight to the previous experiments. The team then graphed and analyzed to the data to determine the accuracy of the balance. Pigging was used to clean the flocculator between all experiments.

Results and Analysis 3

In the first trial, the mass of the flocculator continuously decreased throughout the experiment. The mass decreased at a rate of 0.5704 grams per day, as can be seen in Figure 8 below.

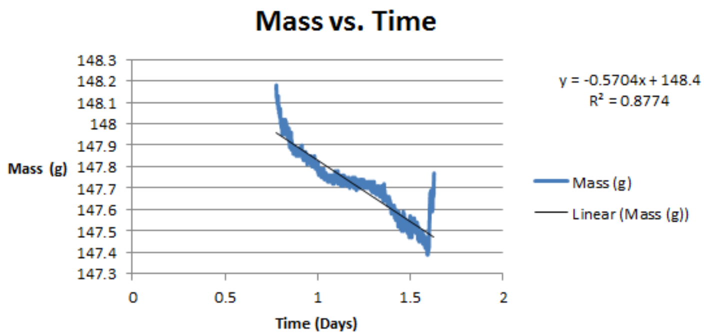

Figure 8: This figure displays the results from the first trial of the third iteration. The mass of the flocculator decreased throughout the experiment.

The team's hypothesis was that the mass of the flocculator would increase due to coagulant buildup on the walls. This hypothesis, however, was not confirmed by the first trial. A possible explanation for the discrepancy would be the tension in the tubing of the flocculator. The tube of the flocculator was connected to a ring stand, as can be seen in Figure 5. The team predicted that for this first trial, the tubes were elevated at a height above the flocculator, causing tension in the tubes. This tension could have altered the mass recordings that were collected. Another possible source of the discrepancy between the team's hypothesis and findings could have been that the balance itself was not giving accurate readings. Before the first trial was run, the team observed that the mass of the flocculator varied greatly over time, even through no outside factors seemed to cause such changes. The team expected the total mass increase of the flocculator over the 24 hour period to be no more that 1.1 grams, so an inaccurate balance could have altered the data for the first trial.

Before the second trial in this iteration, the team adjusted the position of the ring stand so that the endings of the flocculator would be at the same level as the bottom of the flocculator, in order to decrease the tension in the tubes. During this test, however, there was a power outage in the lab so the apparatus stopped running and ProCoDA stopped recording data. The team repeated the second 24 hour trial during the next lab session.

The team also ran a calibration trial so that the accuracy of the balance itself could be tested. In this trial, only water was run through the apparatus for approximately 17 hours. The mass of the flocculator was continuously recorded over this time period. As can be seen in Figure 9 below, the mass of the flocculator did fluctuate over time, but the change in mass was 0.0162 grams over the course of the experiment. Since the change in mass of 0.0162 grams was so small, the team could neglect the change when measuring the mass of the flocculator over time.

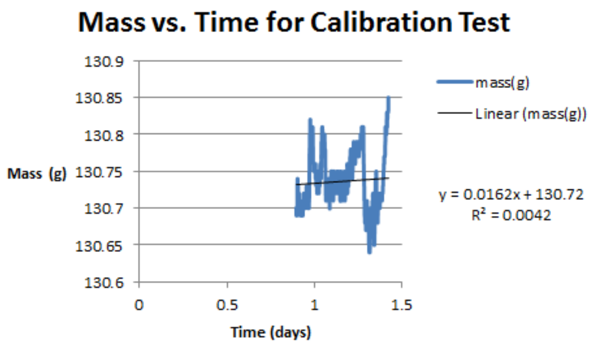

Figure 9: This figure displays the result of the calibration test, in which only water was pumped through the apparatus for 17 hours. The mass of the flocculator was relatively constant over the experiment time.

Because the slope of the graph was 0.05, the team concluded that the inaccuracy of the balance was not the cause of the decrease in mass of the flocculator for the first trial of the iteration. The team could not determine the cause of the mass decrease, so the team turned to another experimentation method.

Fourth Iteration

For the fourth iteration, the team constructed a tube settler and changed the method of testing from mass balance to measuring the turbidity of effluent water. The team changed the testing method because the mass balance technique did not produce consistent results. The goal of the fourth iteration was to set the influent turbidity at 5 NTU and measure the effluent turbidity throughout the experiment. The team was looking to see a consistent performance of the tube settler, as measured by pC*, throughout the experiment. The equation (2) for pC* is as follows:

$$pC* = \frac{9}{8}\log\frac{8}{9}\frac{6}{\pi}^{\frac{8}{9}}\pi k\Gamma\phi_0^{\frac{8}{9}}\frac{t\epsilon^{\frac{1}{3}}}{d_p^{\frac{2}{3}}}+1 \tag{2}$$

The team used a simplified version, equation (3), which was:

$$pC* = -\log\frac{Effluent\ Turbidity}{Influent\ Turbidity} \tag{3}$$

Experimental Apparatus 4

A tube settler was added to the apparatus after the mass balance technique failed to give consistent results. The tube settler was added after the flocculator, and the turbidity of the effluent water was measured after flocs settled out at the bottom of the tube settler. A valve was used at the bottom of the tube settler to drain the flocs in between tests. Pigging was still used to clean the flocculator in between tests.

The tube settler was angled at 45 degrees and was 0.556 meters long. The tube used was 1 inch in diameter and the capture velocity, v_c, was 0.12 mm/s, based on the AguaClara plant value. The 45 degree angle was chosen for ease of construction and the length of the tube settler was calculated based on this angle:

$$v_\alpha = \frac{Q_{plant}}{\frac{\pi (D_{TubeSettler})^2}{4}} \tag{4}$$

$$v_{plate} = v_\alpha \sin\alpha \tag{5}$$

$$L_{TubeSettler} = \frac{\frac{v_{plate}}{v_c} - (\sin\alpha)^2}{\cos\alpha \sin\alpha} D_{TubeSettler} \tag{6}$$

The tube settler shown below in Figure 10 had a full length of 0.91 meters. The tube settler was elongated before the second trial of the iteration. For the elongated tube settler, the team drilled a hole 20 cm from the bottom of the tube settler, which served as the inlet of the water from the flocculator. The space above the inlet was 0.7 m long, which was larger than the 0.556 m that it took for the flocs to settle out. The 20 cm below the inlet served as a small sedimentation tank where the flocs eventually settled in.

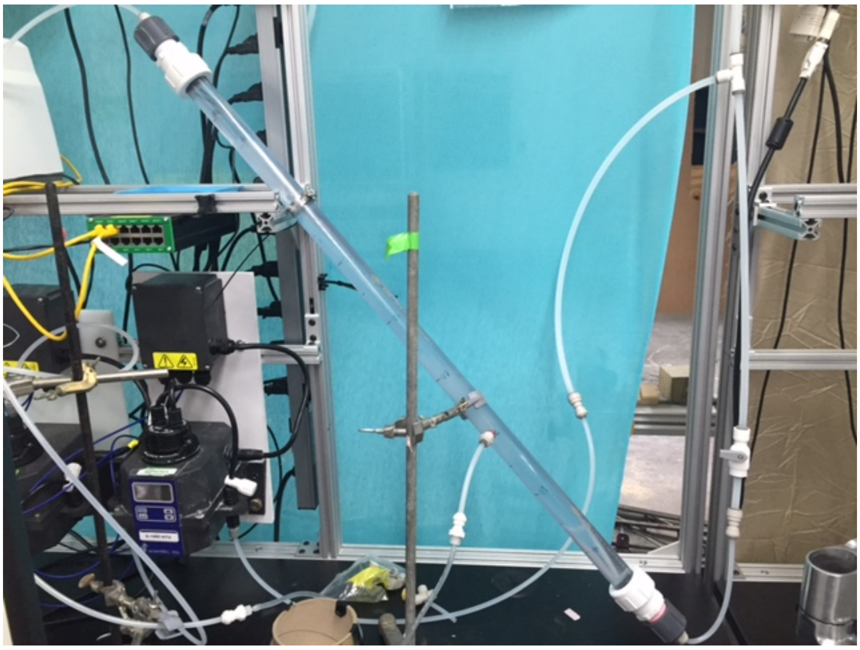

Figure 10: This figure shows the tube settler constructed by the team. After water flows through the flocculator, it enters the tube settler through the inlet (about a third of the way up) and flocs settle out and clean water exits the top of the tube.

ProCoDA Methods 4

The team added two variables to ProCoDA in order to measure the influent and effluent turbidities during the experiments. The team added these variables so that turbidities could be recorded every 60 seconds. Since the team no longer used mass balance, the mass variable was removed from ProCoDA.

- Influent Turbidity: The variable recorded the influent turbidity, measured from the clay solution, every 60 seconds during a test.
- Effluent Turbidity: The variable recorded the effluent turbidity after the water passed through the tube settler every 60 seconds during a test.

Procedure 4

When the team changed their experimentation technique from mass balance to the tube settler, the team changed the length of the tests from 24 hours to six hours. This was done so that the team could run more tests per week, and because the team didn't need a 24 hour test for data to become visible. In other words, the team was looking to see the tube settler performing consistently for at least two hours. The team measured the consistency of the tube settler's performance using pC*, equation (3). After each test the tube settler was emptied to remove flocs that had settled out at the bottom. The procedure for tests involving the tube settler can be seen in the Standard Operating Procedure, above.

Results and Analysis 4

For the first test conducted with the tube settler, the team observed that the tube settler had a consistent turbidity difference between influent and effluent of 4.5 NTU for one hour and then the tube settler hit breakthrough and the NTU difference became negative. The pC* values for the entire six hour experiment can be seen in Figure 11. Since the first hour of the test showed that the tube settler was performing consistently, the graph of pC* versus time for only the first hour were graphed in Figure 12. The team predicted that the tube settler hit breakthrough because eventually, the flocs that were produced flowed out through the top of the tube settler and into the turbidity meter. This caused the effluent turbidity reading to increase dramatically, which meant that the difference between influent and effluent turbidities became negative. As a result, the negative pC* values that can be seen in Figure 11 were attributed to the tube settler hitting breakthrough.

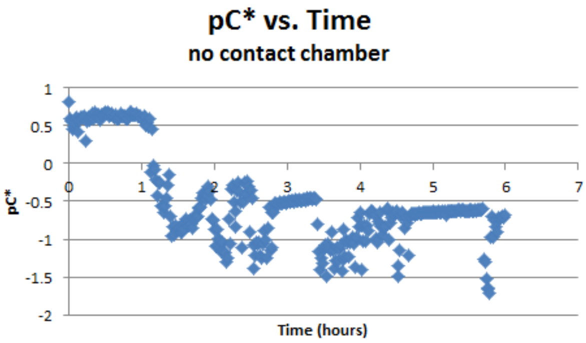

Figure 11: This figure displays the pC* values for the first trial of the experiment with the tube settler. The experiment was run at the same initial conditions as the previous experiments: 5 NTU influent turbidity and a 2 mg/L coagulant dose. The team predicted that the tube settler hit breakthrough after one hour of the experiment.

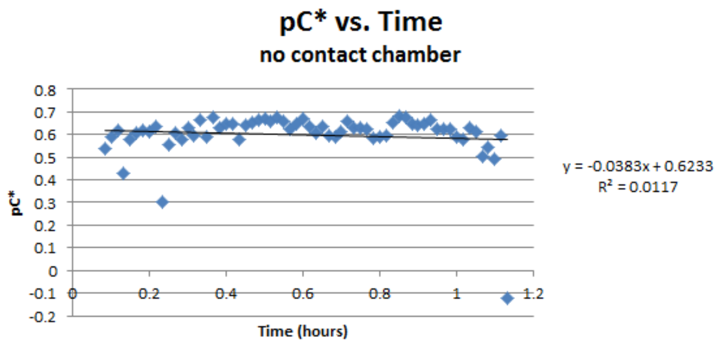

Figure 12: This figure displays the pC* values for only the first hour of the experiment, during which time the performance of the tube settler was relatively constant, as can be seen by the zero-sloped graph.

In order to improve the apparatus, the team elongated the tube settler to 0.91 meters. The team did so because they predicted that a longer tube settler would prevent it from hitting breakthrough so early on in the experiment. In the longer tube settler, the influent water flowed in through the side of the tube settler instead of the bottom, as can be seen in Figure 10, and approximately 20 cm of tubing were below the inlet. This space was for the flocs to accumulate.

The second trial, which used the longer tube settler, resulted in the tube settler performing consistently for two hours and then hitting breakthrough. The performance of the tube settler was again measured by pC*. As can be seen below in Figure 13, the pC* values were consistent for two hours and then fluctuated because the tube settler hit breakthrough:

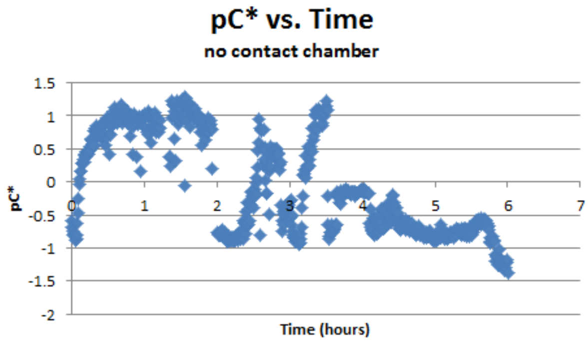

Figure 13: This figure displays the pC* values, or the negative log of the effluent over influent turbidites. The pC* values were measurements of the performance of the tube settler. The team observed a steady performance for approximately 2 hours, until the tube settler hit breakthrough.

The initial increase in pC* was due to the time it took for the clay and coagulant mixture to flow through the apparatus and reach the effluent turbidity meter.

If the first two hours of the experiment were graphed, it can be seen that the pC* values were fairly consistent.

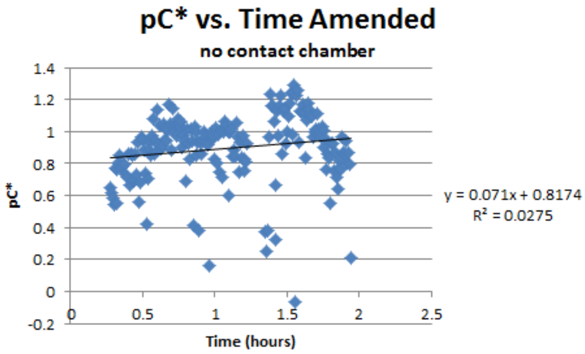

Figure 14: This figure displays the pC* values for the first two hours of the experiment, during which time the performance of the tube settler was relatively constant.

The team predicted that if a contact chamber were to be added to the apparatus, the pC* values for this experiment would be above 0.8 and constant. This would mean that due to the contact chamber, the effluent turbidity was lower, which would make the pC* higher. Since pC* is a measure of performance, a higher pC* would mean better performance and that the contact chamber would reduce coagulant loss. The results shown in Figure 14 were promising because they showed that the tube settler could be used to record the pC* of apparatus. Since the pC* was constant, i.e. could be modeled as a line with a slope of approximately zero, the pC* of the apparatus without a contact chamber could be easily compared with the pC* of other apparatuses, i.e. ones with contact chambers.

Fifth Iteration

In the fifth iteration, the team tested different designs of contact chambers. Three designs as well as a control apparatus were tested. The data from these tests showed the best designs for a contact chamber and the effectiveness of adding a chamber on the performance of the tube settler. The testing procedure developed in the fourth iteration was used for tests in this iteration. ProCoDA methods did not change.

Experimental Apparatus 5

The team built three contact chamber to test for the fifth iteration. Two of the contact chambers had equal volumes but different diameters and, thus, different surface areas. As shown in Figure 15 , the chambers were made out of PVC pipe and connectors. The jets were made by drilling a hole in a connector cap and weaving tubing through the apparatus.

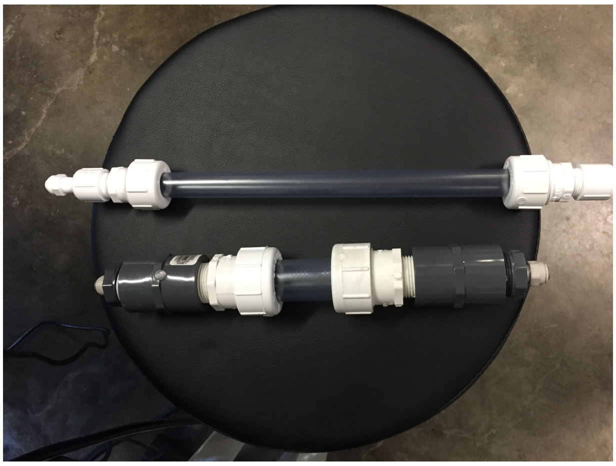

Figure 15: This figure shows the two contact chambers designed and built by the team. The residence time and volume for both were the same; however, radius differed. The contact chambers will be used to test the impact surface area of the contact chamber has on coagulant loss.

The team designed the parameters of the contact chambers based on residence time, which should be greater than the time spent in the flocculator ($18.6s$), but not excessively large. Consequently, the team made the residence time 1 minute. The team designed the diameter of the orifice on the connector cap so that the head loss would be no larger than 1 m. Equation (8) was used to calculate the diameter of the orifice. ϵ_{Max} is the maximum energy dissipation rate, and the team calculated ϵ_{Max}based on Equation (7):

$$h_e = \frac{\left(\frac{4\Pi_{JetRound} Q \epsilon_{Max}^2}{\pi}\right)^{\frac{2}{7}}}{2g\Pi_{JetRound}^2} \tag{7}$$

$$D_{orifice} = \left(\frac{4Q\Pi_{JetRound}}{\epsilon_{Max}^{\frac{1}{3}}\pi}\right)^{\frac{3}{7}} \frac{1}{\sqrt{\Pi_{vc}}} \tag{8}$$

The first two contact chambers had the same volume but different surface areas. The first contact chamber had a length of 11.6 cm and an inner diameter of 2.54 cm. The second contact chamber had a length of 32.35 cm and an inner diameter of 1.52 cm.

The third contact chamber that the team designed had a different volume than the first two contact chamber, so that the team could test whether the residence time of the apparatus affected the efficiency of the tube settler. The team designed the third contact chamber so that it had a length of 30.5 cm and an inner diameter of 2.54 cm.

The team also ran a test in which the total residence time of the apparatus with and without the contact chamber was kept the same. A 3.8 m and 0.44 cm inner diameter tubing was added to the apparatus in place of the contact chamber. The tubing was added before the flocculator. The addition of the tubing resulted in the overall apparatus having the same residence time as the apparatus including a contact chamber. By constructing an apparatus which had the same residence time as an apparatus with a contact chamber, the team was able to determine whether the increase in residence time because of the addition of the contact chamber was a confounding variable.

Procedure 5

For these iterations the contact chambers were tested, and the team followed the procedure outlined in the Standard Operating Procedure above. The team used ProCoDA to record the influent and effluent turbidities every 5 seconds during the test, instead of every 60 seconds. The change was made in order to obtain more data points so that the consistency of the tube settler could be more accurately traced.

Results and Analysis 5

The graph in Figure 16 displays a comparison of two controls: the first control was performed by not adding extra tubing to the non-contact chamber apparatus, or not accounting for residence time; the second, by adding the residence time of the contact chamber in the tubing of the apparatus.

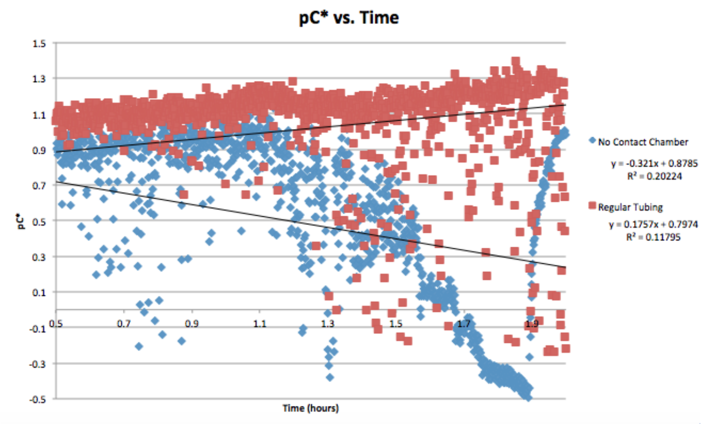

Figure 16: This figure compares the pC* over time for two apparatuses with no contact chambers. The first apparatus (displayed in blue) had neither a contact chamber nor extra tubing. The second apparatus (displayed in red) had regular hard tubing added to account for the increased residence time in the apparatus when a contact chamber is added. The second apparatus did not have a contact chamber either. The test was performed to demonstrate whether or not added residence time is a confounding variable.

Figure 16 demonstrated that adding residence time to account for the residence time of the contact chamber increased the performance of the tube settler. The apparatus that did not account for residence time (shown in blue in Figure 16) had a lower pC* and failed earlier. Therefore, later analysis used the regular tubing that accounted for residence time as a control since it account for added residence time.

Figures 17 and 18 represented two trials of a comparison of all of the contact chambers. The efficiency of the tube settler with the control, the apparatus with additional hard tubing, was also tested in both trials. All tests were run following the Standard Operating Procedure outlined above. There was an unintended spike in influent turbidity in the second trial of the 0.6 inch diameter contact chamber for less than 0.1 hours so those points were removed from the data.

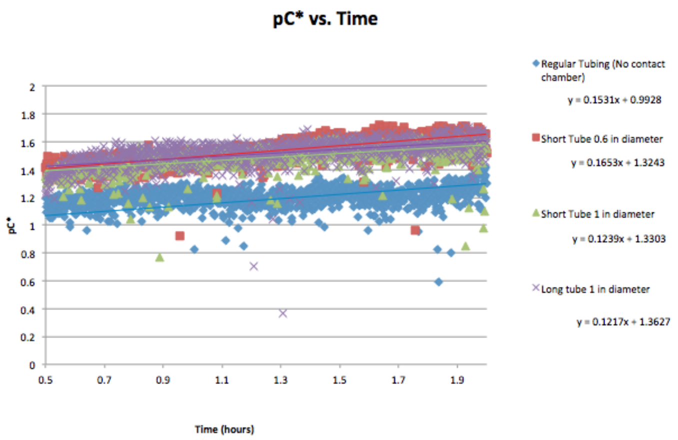

Figure 17: This graph is the first trial of a comparison of the different contact chambers built by the team. The regular tubing parameter is the control. The three contact chambers varied radius and residence time. From this the optimal contact chamber design could be inferred.

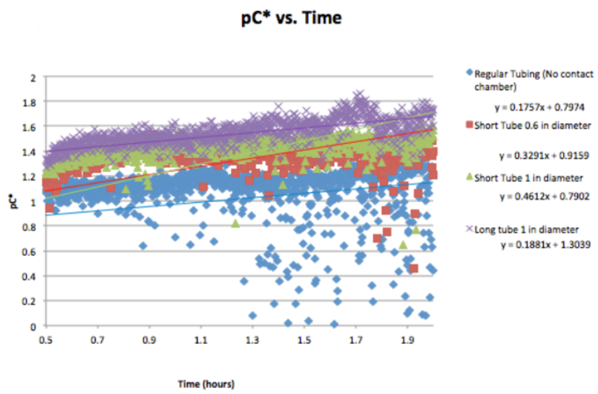

Figure 18: This graph is the second trial of a comparison of the different contact chambers built by the team. This was done to show the consistency of the data.

The graphs showed the impact of adding a contact chamber. The control or regular tubing preformed noticeably worse than all of the contact chambers in both trials, as can be seen by the lower pC* of the control apparatus. Also, as can be seen in Figures 17 and 18, the pC* values for the three contact chambers being tested were very similar to each other. In other words, the team was unable to determine the most effective contact chamber by merely looking at the plots of pC* for each of the contact chambers, because the pC* values were very close for all three.

In order to determine which contact chamber was most efficient, the average pC* value for each contact chamber was determined for each of the two trials. The results can be seen in Table 2. The first column of Table 2 represents the experiments shown in Figure 17 and the second column represents the experiments shown in 18.

Table 2: Average pC* for contact chambers

Contact Chamber	Average pC* Run 1	Average pC* Run 2
Regular Tubing (0.175 in diameter)	1.197	1.058
Short Tube (0.6 in diameter)	1.531	1.383
Short Tube (1 in diameter)	1.485	1.431
Long Tube (1 in diameter)	1.515	1.550

As can be seen in Table 2 above, for both of the trials, the apparatus without a contact chamber performed considerably worse than the apparatuses with contact chambers. The observed result occurred because without the contact chamber, the coagulant was less likely to stick on clay particles. Therefore fewer and smaller flocs were made and those flocs were not removed in the tube settler, leading to a lower pC* or worse performance. In addition, the long contact chamber seemed to have performed better than the shorter contact chambers, as evidenced by the larger pC* values for the longer contact chamber. However, as can be seen in the first column of Table 2, the short contact chamber with a 1.52 cm diameter performed better than the long contact chamber did in Trial 1.

Since it was difficult to determine which contact chamber was most efficient from Figures 17 and 18, and because the average pC* values also yielded mixed results, Figures 19 and 20 were constructed to show a closer comparison of the three contact chambers.

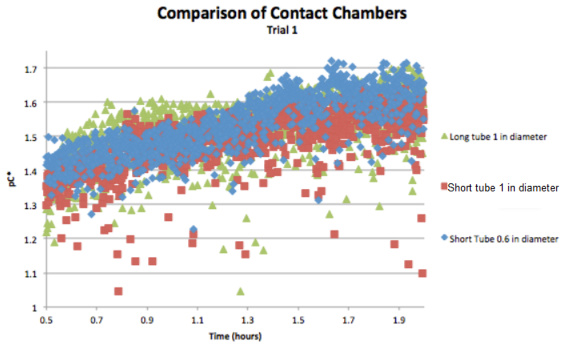

Figure 19: This graph is the first trial of a test that compared the three contact chambers built by the team. The three contact chamber differed in residence time or radius as shown on the graph. From this information the team could determine the best shape for a contact chamber.

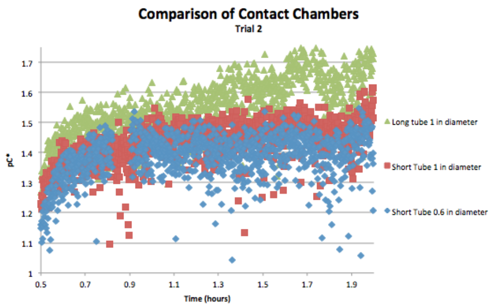

Figure 20: This graph is the second trial of a test that compared the three contact chambers built by the team. This was done to show the consistency of the data.

As can be seen in Figures 19 and 20 and from Table 2, the longer contact chamber was the most efficient. Thus, the team concluded that residence time in the contact chamber had the biggest effect on performance of the tube settler. The team also observed that when the radius of the contact chamber was increased from the regular tubing (0.44 cm) to the 1.52 cm diameter contact chamber, the efficiency of the tube settler increased dramatically. However, when the radius of the contact chamber was increased again from 1.52 cm to 2.54 cm, a smaller increment, the efficiency of the tube settler did not increase by as much. As a result, the team determined that although the radius of the contact chamber affected the pC* values, the effect was not as blatant or large as the effect of varying the residence time of the contact chamber.

Conclusions

The tests demonstrated that contact chambers improved the performance of the tube settler, thereby reducing the amount of coagulant lost to the walls of the apparatus. The data showed that all of the contact chamber designs had a better pC* than the control. The team inferred that the increased pC* was the effect of less coagulant being lost to the walls. Therefore contact chambers reduced the loss of coagulant to the walls of the apparatus.

In the fourth iteration, the two tests performed using the tube settler showed that the tube settler was performing consistently for approximately one to two hours before hitting breakthrough. The team concluded that measuring pC* values without a contact chamber was effective and accurate, because the tube settler was performing consistently for an appropriate period of time. The team also concluded that one to two hour tests could be performed with a contact chamber in the future, and the pC* values could be compared to the pC* values for the apparatus without the contact chamber. All of the iterations also revealed that pigging was a suitable method of cleaning the flocculator, because the mass of the flocculator before running the test and after cleaning the flocculator was approximately the same.

After determining that contact chambers were effective, the team tested two variables in contact chamber performance. The first was residence time. Residence time was tested by constructing the long and short contact chambers which had the same radius. The longer contact chamber consistently performed better than the shorter one. The results reflected and validated the team's hypothesis: that increased residence time would decrease coagulant loss because there would be a larger volume in which coagulant and clay particles could collide. Therefore, the team concluded that residence time was a key factor in designing an effective contact chamber.

The second variable tested was the radius of the contact chamber, which determined the surface area to volume ratio. Testing of the radius variable did not yield definitive results. One of the tests had a slight favor to a larger radius where the second test demonstrated that the contact chambers of different radii performed evenly. The team had predicted that the larger radius would result in less coagulant being lost to the walls of the apparatus, because there was less wall space compared to water volume so the coagulant would be more likely to hit a clay particle than a wall. The results showed that the radius had an effect on contact chambers' effectiveness only to a limit: contact chambers with very small radii (like the 0.175 inch regular tubing) performed much worse than average radii (0.6 inch). However a variation from a 0.6 inch radius to a 1 inch did not produce a dramatic increase in efficiency.

The results did not show that radius has a large effect on contact chambers' effectiveness, but showed that more testing would be needed to make a full conclusion. Overall, however, the team recommended that contact chambers should be added to AguaClara plants to improve their efficiency.

Future Work

Future work in contact chambers for an AguaClara plant would be to determine how the radius or the surface area to volume ratio impacts the efficiency of the apparatus and to try a model contact chamber in a larger scale plant. The current team's data showed mixed results with changes in radius. A very small radius decreased efficiency while a change in diameter form 0.6 to 1 inch had barely any difference. Testing a wider range of radii will allow the team to be able to determine how the radius of a contact chamber affects the efficiency of the apparatus. Testing a larger model will also determine how the results can be scaled up. Also at a larger scale, cylindrically shaped contact chambers may not be as cost effective or easy to build as they are at a smaller scale. In other words, at a larger scale, different shapes of contact chambers can be tested. Recommendations include a cube or sphere that would be hard to test on such a small scale.

References

Chu, T., Li, L., and Harris, J. (2016). StaRS Filter Theory, Spring 2016 - Overleaf.

Eden NC (2011). Water and Wastewater Treatment Facilities.

Semerci, N. (2012). Design of Ozone Contact Chamber.

Swetland, K. (2012). Rapid Mix Tube.

Weber-Shirk, M. (2015). Coagulation and Rapid Mix: A search for a basis for rational design.

Semester Schedule

Task Map

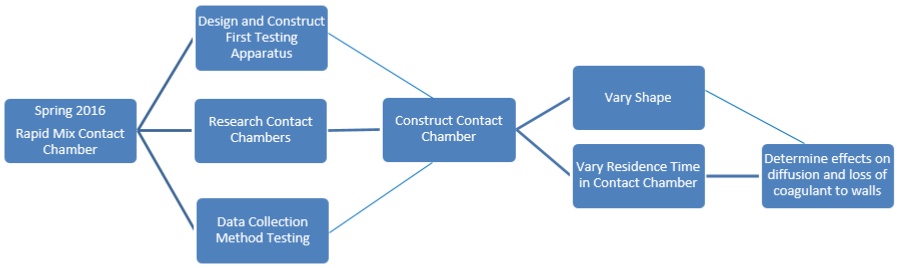

Figure 21: TaskMap

Task List

1. Design and Construct First Testing Apparatus by 3/1/16 (Jillian Whiting): The team's first testing apparatus is only the rapid mix of clay, water, and coagulant and a flocculator. This apparatus will be designed using MathCad for exact specification calculation. This apparatus will be used to test the current data collection method or mass balance. -Completed

2. Research Contact Chambers by 3/1/16 (Aditi Athavale): Look at past AguaClara Rapid Mix designs as well as CEE 4540 notes and outside information on contact chambers to guide the research.-Completed

3. Data Collection Method Testing by 3/15/16 (Alick Zu): Test the planned data collection method of mass balance with pigging and/or an acid wash between tests. Repeat this until reproducible testing and cleaning method is achieved.-Complete

4. Construct Contact Chamber by 3/23/16 (Jillian Whiting): Construct preliminary design for contact chamber, making sure that the system can be run with and without (bypassing) it.- Complete

5. Vary Shape of Chamber by 4/12/16 (Jillian Whiting): Change the geometry and shape of the contact chamber to determine best shape and how shape affects rapid mix. -Complete

6. Vary Residence Time in Contact Chamber by 4/29/16 (Aditi Athavale): Change residence time to see how diffusion and coagulant loss varies with time -Complete

7. Determine effects on diffusion and loss of coagulant to walls by 5/11/16 (All group members): Write up final report on best design for a contact chamber as well as theoretical reasons behind it.-Complete

Report Proofreader: Aditi Athavale