Flocculation/Sedimentation Optimization Final Report

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1 Introduction

The Flocculation and Sedimentation team's primary goal this semester was to introduce floc recycle into AguaClara plants, to research and evaluate the performance of the water treatment plant as a result. By recycling already wasted flocs and injecting them into the system at the beginning of the flocculation process, collision potential will increase and flocs will form earlier in the process. Improvement in effluent turbidities was excepted.

To begin the process the team first had toreliably build a floc blanket using PACl as a coagulant. Previous teams had difficulty building floc blankets with alum due to improper dosing and loss of coagulant to the walls of the flocculator. To reduce the loss of coagulant to the walls of the tubing, the team replaced the rapid mix chamber with a large diameter reactor that acts as a contact tank with mixing provided by a hydraulic jet. This reactor completely mixes the raw water and coagulant before it arrives at the flocculator.

In order to better evaluate floc blanket behavior and floc recycle, the team designed and installed a backlight for the sedimentation tank, and a camera that can detect the height of the floc-water interface in the sedimentation tank. This allowed the team to observe floc blanket behavior while not present in the lab and further modify experiments as a result.

Once these preliminary actions were taken the team began introducing floc recycle to the plant. Flocs were drawn from the floc weir when a floc blanket had fully formed and entered into the beginning on the flocculator to allow clay to adhere to previously formed flocs. The team varied coagulant dose and up flow velocity used to build the floc blanket, as well as where flocs were drawn from throughout the length of the sedimentation tank.

The research on floc recycle in AguaClara plants this semester will result in the knowledge of proper coagulant dosing for the synthetic raw water used in the laboratory and the reliable buildup of floc blankets in sedimentation tanks, as well as how to optimize already wasted flocs. The end goal is to determine if floc recycle will enhance performance of AguaClarawater treatment plants, and if so, is introducing floc recycle into full scale AguaClara plants to optimize the water treatment process a realistic possibility.

2 Literature Review

2.1 Coagulant: PACl vs. Alum

Alum (aluminum sulfate) is a commonly used coagulant in water treatment plants, largely because of its low cost. However, there are many limitations to using alum such as its limited pH range, which must be between 5.5 and 6.5 for coagulation, the high residual aluminum levels in the treated water and the fragility of the alum floc produced.

Recently, aluminum-based coagulants have been developed for water treatment such as polyaluminum chloride, or PACl. PACl is an inorganic polymer coagulant that is effective over a pH range of 5.0 to 8.0. PACl is also advantageous because there is a lower residual aluminum levels in treated water, improved overall treated water quality and lower sludge production.

A jar test, comparing PACl and Alum, was performed to mimic a large sedimentation plant, a short, high speed rapid mix, followed by flocculation and settling. After settling the samples were collected from the from the middle of the jar, 1 cm below the surface. The results show that Alum was more effective in warmer water but PACl still required a lower coagulant dose[4].

2.2 Upflow velocity

The Flocculation Sedimentation Optimization team in the Spring 2012 semester reported that the optimal upflow velocity was determined to be 2 mm/s. The optimal upflow velocity was determined by varying influent turbidity and coagulant (Alum) dose. Influent turbidities were 3 and 500 NTU, and coagulant doses were 15 and 95 mg/L, respectively. The experiments showed effluent turbidities below or approximately at 1 NTU with upflow velocity of 2 mm/s. However, when the upflow velocity was increased to 2.25 mm/s, the effluent turbidity could not be maintained below 3 NTU [1].

2.3 Floc recycle

Floc recycle is thought to improve the effluent turbidity and overall removal efficiency of a water treatment plant. The addition of wasted sludge to the beginning of the coagulation and flocculation process provides more collision potential in the flocculator, thus capturing smaller dirt particles earlier on in the plant.

Recycling sludge was implemented with great success in a water treatment plant in Fort Madison, Iowa. Plant operators noticed very poor plant performance when the water was either very clean during cold weather, or at the other extreme, very dirty after heavy rainfall. The operators began continuously recycling dense sludge from the bottom of the sedimentation tanks using a sump pump straight into the raw water pipes. Since recycling sludge was implemented in the plant, the effluent water quality has improved drastically on both ends of the extreme. A 90% difference was seen between effluent water treated without recycle and water treated with sludge recycle, at the range of turbidities tested (2 NTU to 3000 NTU).

Plant operators also found that water taste and odor complaints were greatly reduced, filters in the plant could run longer and be replaced less often, the concentration of bacteria colonies have lowered and thus the demand cost for cholorination in the plant was lowered [3].

The success of floc recycle in improving effluent water quality from this treatment plant has led the Flocculation and Sedimentation Optimization team to believe that AguaClara water treatment plants can benefit from the addition of floc recycling into the entire plant. The Flocculation Sedimentation Optimization team in the Spring 2012 semester made several floc recycle observations. The observations were made with recycle ratio of 0.10 of the plant flow rate and influent turbidity of 3 NTU. The team varied coagulant dose when floc recycle started since coagulant contributes significantly to the AguaClara operating costs. By treating 3 NTU water with 3, 5, 10, and 15 mg/L of Alum, it was observed that lower coagulant dose produced lower effluent turbidity. With 3 mg/L, the observed effluent turbidity was approximately 18 NTU. According to the results, performance worsened with floc recycle compared to that without floc recycle[1].

3 Methods

3.1 Apparatus

The experimental setup with the changes of the new rapid mix chamber and back lighting are shown below on figure 1.

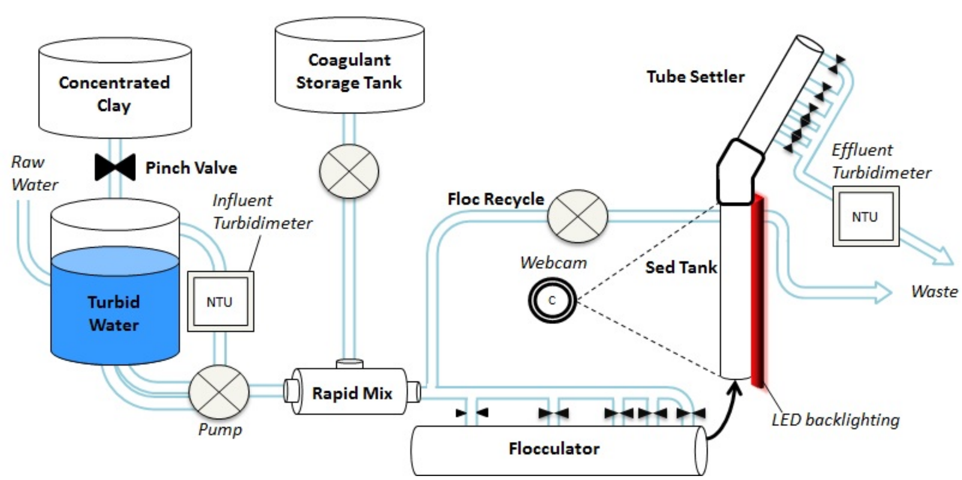

Figure 1: Experimental setup

Specifications of the setup are shown below on table 1.

Table 1: Specifications of experimental setup

Parameter	Symbol	Values
Length of tube settler	L_{Tube}	64.2 cm
Inner Diameter of tube settler	D_{Tube}	2.6 cm
Inner Diameter of Pipe into Sedimentation Tank	$D_{FlocToSed}$	0.48 cm
Inner Diameter of Sedimentation Tank	$D_{SedTank}$	2.6 cm
Height of sedimentation tank	L_{Sed}	99 cm
Cross-sectional area of sedimentation tank	A_{Sed}	5.41 cm^2
Inner Diameter of Flocculator	D_{Floc}	0.48 cm
Diameter of Flocculator Coil	$D_{FlocCoil}$	12 cm
Length of flocculator	L_{Floc}	20 m

3.1.1 Cleaning

The first step this team took this semester was to clean out the apparatus. Over the winter break it had collected mold and was unable to operate. The team drained all the water in the tubing and then flushed a solution of water and chlorine through the apparatus to kill all mold and to remove the coagulant from the walls of the tubing. Small pieces of sponge were flushed through the flocculator to remove coagulant and clay that was still stuck on the walls of the tubing. Finally, the team ran clean water to remove any of the chlorine solution left in the tubes.

After every experiment, the team drained the sedimentation tank and cleaned the built up flocs in the flocculator. Basic cleaning of the flocculator includes scraping the tubing to loosen dirt and coagulant stuck to the walls, and flushing out all of the loosened sediment into a bucket. Any clogged or dirty tubes werereplaced routinely; however, the team dicussed replacing the entire flocculator with a new but similar tubing or even changing the tubing to a larger diameter or hydrophobic tubing to avoid having to clean the tubing frequently.

3.1.2 Calibration of peristaltic pumps

The team calibrated the peristaltic pumps to deliver the correct flow rates for the coagulant and the raw water ($Q_{CoagStock}$ and Q_W). The team tested with 5% and 80% of the maximum flow rate that the pumps could handle. Since the maximum flow rate for the pumps in the team was 100 rpm, the calibration values were 5 rpm and 80 rpm. The team calibrated at 80 rpm since pumps ran at 100 rpm when calibrating at 95 rpm.

Although the raw water pump was calibrating correctly, the coagulant pump was not delivering the correct values after saving the calibration values. Therefore, the team changed the stamp box location of the coagulant pump from 1 to 5. With this change, the coagulant pump was calibrated correctly. However, when Process Controller was closed and reopened again after saving the calibrated values, Process Controller lost the calibrated data. Process Controller saved the values in the correct folders, but did not import those values when it was reopened. It was determined that the program for Process Controller was written in a way where it searches for the calibration values in each stamp box, starting at 0. When it does not detect any calibration values for the next stamp box, it would stop importing calibration values. In this case, the raw water pump was plugged into stamp box 0 and coagulant pump was plugged into stamp box 5. Process Controller imported the calibration values for the raw water pump; however, it did not import the calibration values for the coagulant pump since there were no calibration values for stamp box 1 through 4. This problem was fixed by manually editing the saved calibration file. Calibration values for stamp box 1 to 4 were all set to zero. This problem also should be fixed in the new version of Process Controller.

3.1.3 Pressure build up and leaking

During the course of a few experiments, water had been leaking from the very top of the tube that was open to the air, connected to the plate settler at the top of the sedimentation tank. Water level rose up in the sedimentation tank and was unable to drain down the tube from the plate settler into the effluent turbidimeter. Instead, the water continued to rise up the tube and leaked over the top. Originally, it was thought that there was a clog in the tubing between the plate settler and the turbidimeter. When the tubing was taken apart and washed out there were no clogs and the leaking was still happening.

One hypothesis was that too much air was coming in the top of the tubing and building up pressure in the tubing leading to the effluent turbidimeter. Instead of being able to flow freely through the tubing and out to the sink, the water was building up on top of trapped air and eventually leaking out the top of the tubing attached to the plate settler. Before the final water drain into the sink there was another T-joint that is open to the air to relieve pressure. It was thought that if this t-joint was raised to the level of the tube that is currently leaking water, it would control the build up of pressure.

3.1.4 Rapid mix chamber

This semester a rapid mix chamber was added to the experimental setup. It was placed just after the coagulant and raw water pumps and is used to fully mix the coagulant with incoming dirt particles to minimize the amount of coagulant lost on the walls of the flocculator. The team discussed the designs for a reactor with Paul Charles in the Hollister Machine Shop.

Paul drilled through a $\frac{1}{4}$ inch solid plastic rod and then glued stainless steel tubing inside the solid plastic rod (calculations and descriptions for the stainless steel tubing are in section 3.2.2). Therefore, the finished products had the necessary inner diameter for our hydraulic jet and the $\frac{1}{4}$ inch outer diameter to fit into the fittings of the rest of the tubing on the apparatus. This was done for two entrances, the raw water and the coagulant, to the raw water mixing chamber. This tubing was connected to the two entrances of the raw water mixing chamber and the rest of the plant so that raw water and coagulant would enter through hydraulic jets and leave the reactor completely mixed through a 1/4 inch tubing. The new rapid mix chamber with these specifications are shown below on figure 2.

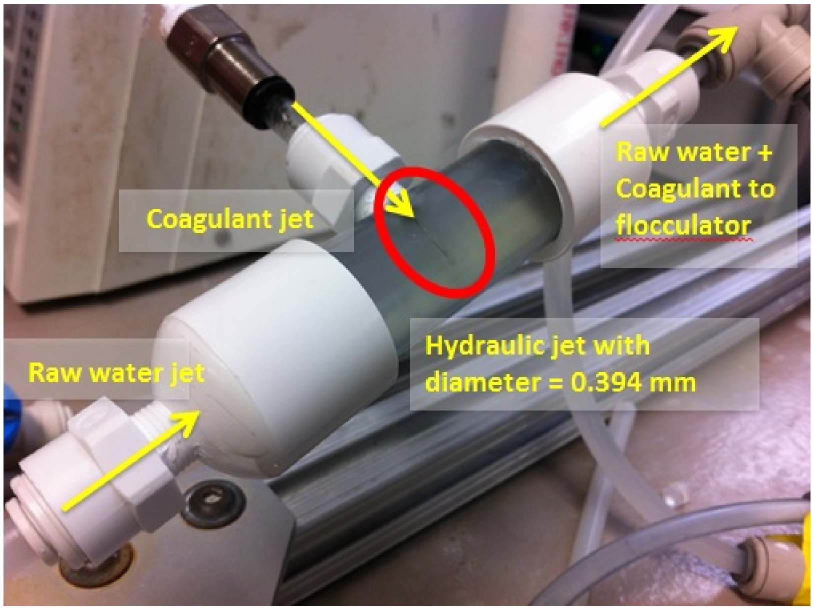

Figure 2: Rapid mix chamber

The team then began flowing water through the plant with the pumps to see if the raw water mixing chamber had any leaks and if the water could properly flow through the chamber into the flocculator. To see how the hydraulic jet diffuser was working the team attached red dye to the coagulant pump and observed how the liquid coming out of the coagulant jet was mixing with the raw water. The red dye diffused thoroughly throughout the reactor and then flowed into the flocculator.

The team began running an experiment with raw water and coagulant flowing through their respective jets and found that within a few hours the jet allowing the raw water to flow into the plant was clogged.

After troubleshooting, it was determined that the water was not flowing through the raw water hydraulic jet into the raw water mixing tank. At first, it seemed that the caluclation for the inner diameter of the jet was incorrect; however, with further observation it was determined that the raw water hydraulic jet was clogged with dirt particles. The tube leading to the rapid mix jet was disconnected and water was flowing through it and the tube after the rapid mix chamber was disconnected and the water flowing was backwash from the flocculator. Therefore, it was determined that the raw water jet was clogged with clay particles and therefore causing the water to circulate back to the water supply.

The team removed the stainless steel tubing and connected the rapid mix chamber to the plastic quarter inch tubing to allow the raw water to flow into the rapid mix chamber without passing through the jet. The coagulant is still being pumped through the jet to enhance mixing. The team realized that 1 m of headloss is not the ultimate constraint when calculating the inner diameter of the jet diffuser, it is the size of the clay particles flowing through the tubing. The next step was going to be to re-design the rapid mix chamber with a jet that has an inner diameter of 1.0 mm. The larger diameter was chosen as a safe value to allow particles through the inner diameter without clogging.

The team confirmed that with only a coagulant diffuser and raw water flowing through 1/4 inch OD tubing, flocs were forming quickly in the flocculator and a fully formed floc blanket was building from these flocs. Therefore, the new 1.0 mm diameter jet was not ordered.

3.1.5 Back lighting for the sedimentation tank

Back lighting for the sedimentation tank is necessary for a web camera to detect the floc water interface and record the height accurately. The team considered many different lighting options including a thin fluorescent tube, a solid lit panel, a diffuser over a strip of LEDs or simply LEDs with a detectable pattern along the back of the sedimentation tank.

The fluorescent lighting option was ruled out due to the high voltage required to light a fluorescent tube which can be unsafe, especially in an environment that contains water. LEDs seemed a logical choice after the voltage was taken into consideration and the team purchased a 48 inch (122 cm) long strip of LEDs that are contained in a plastic casing. The LED lights are red, a monocolor, which should make it easier for a camera to detect the floc water interface.

This light strip was ordered from LEDlight.com and the purchasing information is as follows:

- Product ID: 48769
- Product Name: 48 Inch LED Tube Light Low Voltage 12 Volt DC Switch & Plug
- Attributes: Color - Red
- Price: $79.99

This red light strip was zip-tied to the back of the sedimentation tank, exactly opposite of the camera that will be working to detect the height of the floc blanket as shown on figure 3 below.

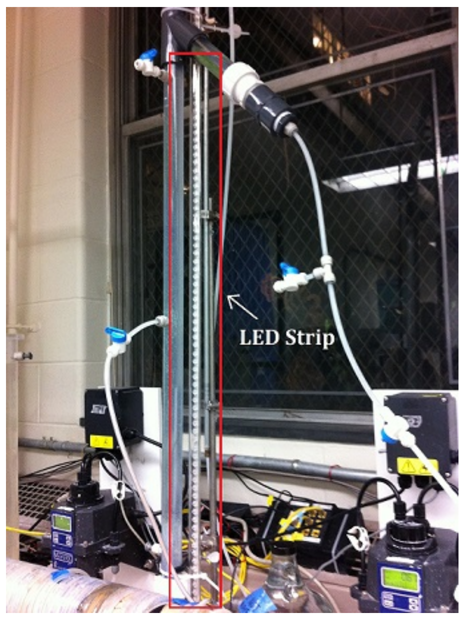

Figure 3: LED back lighting used for optical detection of floc blanket

The team was having difficulties with the light strip being exactly parallel to the sedimentation tank; the floc weir interfered with the positioning on the back of the sedimentation tank. Part of the LED strip was still sticking out of the side of the sedimentation tank. The team raised the height of the sedimentation tank by extending the stand the clamps were attached, so the top of the light strip would fall just under the floc weir and exactly parallel to the sedimentation tank.

The team also changed the position of the camera that was recording images so that it would be in front of the sedimentation tank with the light strip directly behind the tank. The camera was duct taped to the side of the computer; a sturdier way to attach the camera is still needed.

The team added a long square strip of low density polyethylene, as shown in figure 4, which was 48 inches (1.22m) long and attached to the front of the strip of LED lights to act as a diffuser.

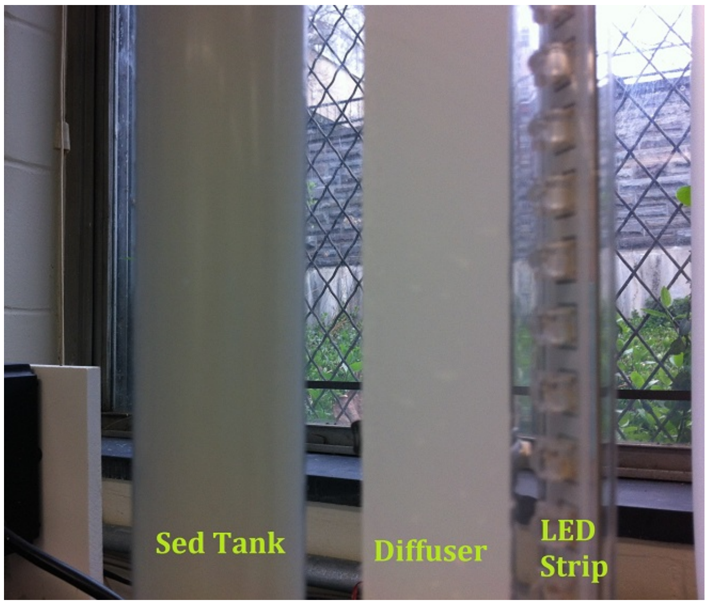

Figure 4: Back lighting with Diffuser

The diffuser was zip-tied to the back of the sedimentation tank, in front of the LED light strip. The diffuser was necessary because the image processing algorithm that intends to detect the floc water interface was detecting the spaces in between the LEDs. With the installation of the diffuser, the light became equally distributed and illuminated the sedimentation tank evenly.

The sedimentation tank with back lighting and diffuser is shown in figure 4.

3.1.6 Integration of the Webcam into Process Controller

Monroe wrote the program Camera Configure and installed it on the computer. First, the placement of the webcam had to be determined, and the side of the sedimentation tank that the camera should face. The team considered building a stand or adding a piece of 80/20 to the frame that currently holds the raw water bucket, but the camera was still too close to the apparatus to capture the entire sedimentation tank . Currently, the webcam is attached to the side of the desktop computer, and the entire sedimentation tank is in the field of view of the camera.

Several settings were changed in Camera Configure to adjust the image as shown in figure 5 below.

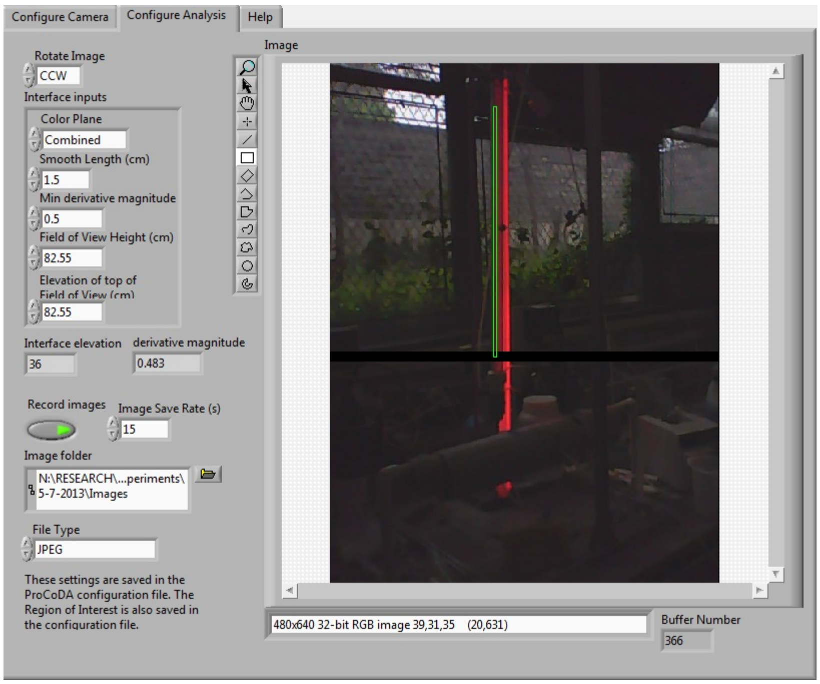

Figure 5: Settings used in Camera Configure

The image was rotated counter clockwise to get the proper view. The image type was changed to JPEG to produce small image sizes. The exposure time was reduced by setting the exposure control to manual and setting the exposure time to 24.4 milliseconds. The reduced exposure time eliminated overexposure of the LED lights. The video mode was also changed to 640×480 MJPG and a new folder to save the images in was created. The field of view was measuring the sedimentation tank. The top of the tank was measured to be 82.55 cm, and now that the top and bottom of the sedimentation tank are in the field of view, the elevation of top of field and the field of view height are the same value. The green box on the image is the range of interest, and the team is going to include the entire sedimentation tank in it. The minimum derivative must also be adjusted so that it will be able to detect the height of the flock blanket, but not other objects that may be in the camera's view. Smooth length is the width of the black line on the image that would detect the height of the floc blanket. Increasing the smooth length would widen the black line and decrease the derivative magnitude. Although it is more accurate to use a smaller smooth length, it may be necessary to increase and adjust it along with the minimum derivative magnitude in order to ignore the objects it sees and successfully detect only the floc blanket height.

Originally when the team ran experiments, the folders would be numbered by date but camera configure would create a dozen folders per experiment. It was established that this was because Camera Configure was reading the folder numbers and then creating subsequent folders. The team started to name the folders "images" instead of by the date of the experiment. Eventually the team realized that the new folders were being created after each time the experiment was started and stopped and after the state changed. The team also decided that it was not necessary to take a picture every 5 seconds and increased the time to 15 seconds between each image. A time lapse video was created to show the growth of the floc blanket over a course of approximately 6.5 hours in windows movie maker for the 5 mg/L experiment, 10 mg/L experiment, and the 20 mg/L experiment.

Two sample images from the webcam from 2:50PM and 6:30PM are shown below on figure 6.

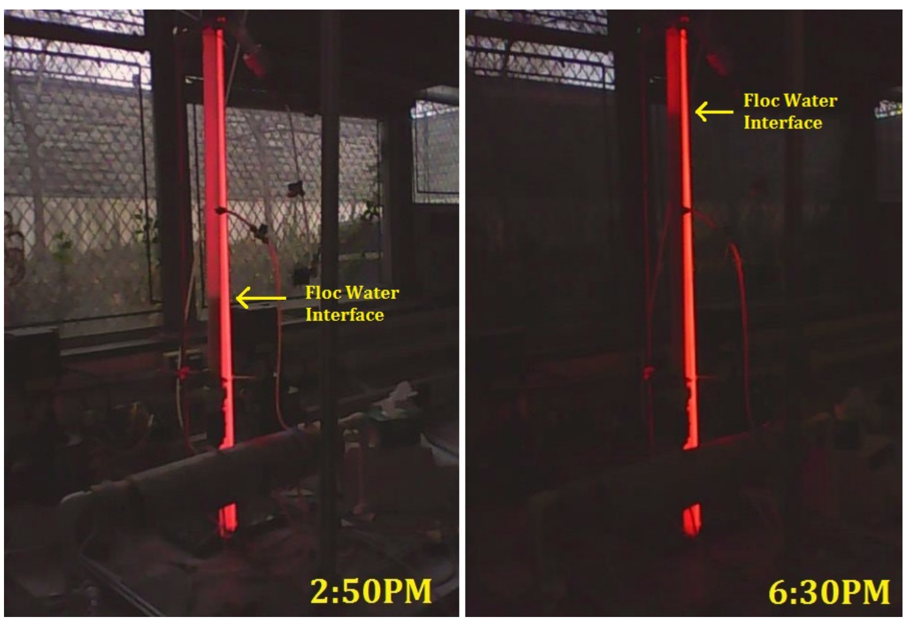

Figure 6: Floc Interface

The growth of the floc blanket is apparent in the images. While the floc blanket is growing, the black line will be at the top of the floc blanket. However, when the floc blanket is at the top of the sedimentation tank, the floc interface will drop to the bottom of the sedimentation tank because it does not see any contrast between the black floc blanket and the red light.

3.1.7 Floc Recycle

It is hypothesized that floc recycle will improve the performance of the plant by adding more flocs for colloids to adhere to in the flocculator. Initially, the tubing to draw flocs to recycle was placed at the bottom of the floc weir and enters the flocculator just after the rapid mix chamber. Other choices for placement included the top, middle and bottom of the sedimentation tank. The bottom of the floc weir seemed to be a logical choice since the flocs being recycled would be already wasted flocs that were not a part of the floc blanket anymore. However, the team found that the floc weir was not filling with flocs or the flocs would be recycled out before they could be replaced and then the recycle pump was recycling clean water being drawn from the top of the floc blanket and the sedimentation tank.

The team decided to allow more time for the floc blankets to build fully before floc recycle began. Instead of the floc recycle pump automatically turning on after a length of one solids residence time, the floc recycle pump would turn on and begin recycling flocs by one of the team members manually switching process controller states when there was a fully floc blanket formed and flocs wasted into the weir. This successfully allowed a floc blanket to build and there to be enough flocs already wasted into the weir for the floc recycle lines to begin drawing from. However the draw back to manually switching states in process controller is that the floc blanket and apparatus had to be continually monitored by member of the team.

3.2 Design Parameters

3.2.1 Coagulant

The team calculated the correct concentration of the stock of PACl to be used in our apparatus with influent turbidity of 100 NTU. Previous teams had been using alum as the coagulant. The team looked at the online data monitoring of the AguaClara plants in Honduras for plants that were dosing with PACl to see what the average dose of PACl for 100 NTU water was. The AguaClara plant in Atima doses with PACl as a coagulant and data from the month of September 2013 indicated that with influent water at 100 NTU turbidity, the average coagulant dose was 10 mg/L [2]. Thus, the team decided to dose the raw water in the experimental apparatus with 10 mg/L of coagulant. By conservation of mass, the coagulant flow rate was calculated as shown in equation 1.

$$C_{CoagStock}Q_{CoagStock} + C_W Q_W = C_{Plant}Q_{Plant} \tag{1}$$

$C_{CoagStock}$ is the stock concentration of PACl, $Q_{CoagStock}$ is the coagulant flow rate , C_W is the concentration in raw water (in this case zero), Q_W is the raw water flow rate , C_{Plant} is the concentration of coagulant in the entire plant (10 mg/L), and Q_{Plant} is the flow rate of entire plant. Since C_W is zero, equation 1 may be simplified as below.

$$Q_{CoagStock} = \frac{C_{Plant}Q_{Plant}}{C_{CoagStock}} \tag{2}$$

Q_{Plant} depends on the the upflow velocity, v_{Sedup}, and the area of the sedimentation tank, A_{Sed}, as shown in equation 3.

$$Q_{Plant} = v_{SedUp}A_{Sed} \tag{3}$$

The team used 1.2 mm/s for v_{Sedup} since it was experimented to be a reasonable value for floc blanket formation this semester. A_{Sed} was calculated to be $5.4\,cm^2$ using its inner diameter from table 1. With these values, Q_{Plant} was determined to be $0.54\,mL/s$.

$C_{CoagStock}$ was determined based on a constraint where $Q_{CoagStock}$ was set to a value greater than the operating range of the peristaltic pump. The pump would stop and return a flow rate of zero if $Q_{CoagStock}$ was set to a lower value than the operating range of the pump, such as 1 or 2 rpm. The minimum and maximum rpm that the team planned to run the pump was at 5 rpm and 80 rpm (see section 3.1.2). With these flow rates and C_{Plant} of 10 mg/L, the required $C_{CoagStock}$ would be 160 mg/L. The team decided to set $C_{CoagStock}$ at 1 g/L, a higher value than required, so that it would have longer durations between refills.

Using these values and equation 2, $Q_{CoagStock}$ was determined to be $5.4 \times 10^{-3} mL/s$. Then, in order to see the performance difference, the team selected a lower and higher PACl dose of 5 and 20 mg/L. Also, higher v_{Sedup} were selected because floc blankets were collapsing at v_{Sedup} of 1 mm/s. Several experiments were done with v_{Sedup} of 1.2, 1.5, 1.8, and 2.0 mm/s. By varying PACl dose and v_{Sedup}, values for the flow rates varied from what was calculated above.

3.2.2 Rapid Mix Chamber

The team calculated the diameter for the hydraulic jets with the design parameter that the orifice had to create 1 m of headloss. The team used 1 m for headloss to ensure the pressure buildup at the pumps would not be excessive.

The team calculated the diameter of the orifice using equations 4, 5, and 6.

$$H = \frac{v_{Jet}^2}{2g} \tag{4}$$

$$Q_{Plant} = v_{Jet}A_{jJet} \tag{5}$$

$$A_{Jet} = \frac{\pi}{4}d_{Jet}^2 \tag{6}$$

H is the 1 m head loss, g is the standard gravity, v_{Jet} is the velocity of the hydraulic jet, A_{Jet} is the cross-sectional area of the jet, and d_{Jet} is the diameter of the jet.

Reorganizing equation 2, v_{Jet} was calculated to be 4.4 m/s. With this value and Q_{Plant} as 0.54 mL/s, $A_{Jet}$was calculated to be $1.2 \times 10^{-7} m^2$ using equation 6. Finally, using equation 4, $d_{Jet}$was calculated to be 0.39 mm.

After calculating the appropriate diameter of the tubing needed to construct the hydraulic jet for the raw water and coagulant entrances to the reactor, the team ordered Precision Miniature Stainless Steel Tubing from McMaster-Carr. The tube ordered has an inner diameter of 0.036 cm and an outer diameter of 0.056 cm. The catalog number is 8987K426.

3.2.3 Flocculator

The specifications of the flocculator is shown in table 1. The velocity gradient, G, was calculated by equation 7 below.

$$G_{Coiled} = G_{Straight}(1 + 0.033(\log(De))^4)^{\frac{1}{2}} \tag{7}$$

G_{Coiled} is the velocity gradient for a coiled flocculator, $G_{Straight}$ is the velocity gradient for a straight tube, and De is the Dean number. $G_{Straight}$ and De were calculated using equations below, respectively.

$$G_{Straight} = \frac{8Q_{plant}}{3\pi r_{Floc}^3} \tag{8}$$

$$De = \frac{v_{SedUp} D_{Floc}}{\nu} \left(\frac{D_{Floc}}{2D_{FlocCoil}} \right)^{\frac{1}{2}} \tag{9}$$

r_{Floc} is the inner radius of the flocculator, D_{Floc} is the inner diameter of the flocculator, $D_{FlocCoil}$ is the diameter of the flocculator coil, ν is the kinematic viscosity of the fluid, $10^{-6}\ m^2/s$ at $20°C$. De was calculated to be 0.82, and there was no significant difference between $G_{Straight}$ and G_{Coiled} and they were calculated to be 40. s^{-1},.

3.2.4 Sedimentation tank

The hydraulic residence time, θ, was calculated using equation 10 below.

$$\theta = \frac{V_{Sed}}{Q_{Plant}} \tag{10}$$

V_{Sed} is the volume of the sedimentation tank and V_{Tube} is the volume of the tube settler, and these were calculated by equation 11 and 12, respectively. which is calculated by equation 11.

$$V_{Sed} = L_{Sed} A_{Sed} \tag{11}$$

$$V_{Tube} = L_{Tube} A_{Tube} \tag{12}$$

V_{Sed} was calculated to be $0.54L$ and V_{Tube} was calculated to be $0.35L$. With Q_{Plant} of 0.65 mL/s (V_{SedUp} of 1.2 mm/s), θ was determined to be $1.4 \times 10^3\ s$.

3.2.5 Tube Settler

The capture velocity, $v_{Capture}$, was calculated using equation 13 below.

$$v_{Capture} = \frac{v_{TubeUp}}{\frac{L_{Tube}}{D_{Tube}} cos\alpha sin\alpha + sin^2\alpha} \tag{13}$$

v_{TubeUp} is the upflow velocity in the tube settler, which is equivalent to v_{SedUp}. α is the angle of the tube settler, 60°. L_{Tube} is the length of the tube settler, 64.2 cm. D_{Tube} is the inner diameter of the tube settler, 2.6 cm. With these values, was calculated to be 0.105 mm/s.

3.2.6 Floc Recycle Ratio

Floc are being recycled at 10% of the v_{SedUp} (orQ_{Plant}) in the sedimentation tank. The floc recycle flow rate,Q_R, was calculated by multiplying the recycle ratio,$\Pi_{Recycle}$, and Q_{Plant}. Since $\Pi_{Recycle}$ would not be varied, this equation can be written as equation 14 below..

$$Q_R = 0.10Q_{Plant} \tag{14}$$

When flocs are being recycled and the floc recycle pump is on, the flow through the sedimentation tank increases by 10% when the floc recycle line is added to the tube carrying raw water up into the plant. In order to take into account the additional flow rate, Q_{Plant} was forced to decrease to $Q_{NewPlant}$ by the amount of the additional flow of Q_R as shown in equation 15.

$$Q_{NewPlant} = Q_{Plant} - Q_R \tag{15}$$

3.2.7 Floc Breakup

After running multiple experiments the team noticed that adding in floc recycle to the entire plant did not make a noticeable difference or was actually making the effluent turbidity higher than it had it been without flocs recycling. One of the hypotheses considered was that the flocs being recycled into the beginning of the flocculator had actually reached their maximum size and therefore the dirt particles in the influent raw water were unable to adhere to the existing flocs coming into the flocculator, and the full flocs were taking coagulant that was being dosed right before the floc recycle entry point. If this is the case that would mean those dirt particles were not forming flocs and will take much longer to settle out of the water.

The team decided to add a clamp as showin in figure 7to the floc recycle line right before the flocs are introduced to break up the fully formed flocs to allow them to continue to grow in the flocculator.

Figure 7: Clamp added to Floc Recycle Line

To determine how tight the clamp should be, a pressure sensor was installed next to the floc recycle pump and then plugged into the bottom row of the port, on channel SC1Mod2/ai0. The pressure sensor originally was reading 200 cm of head, total head due to the height of the water column in the sedimentation tank plus head loss in the flocculator when installed and the clamp was not tightened. Using the pressure sensor readings in Process Controller, the clamp was tightened until there was 300 cm of head in the floc recycle line.

After the floc recycle pump was left to run at 300 cm of head for roughly one hour it was found that the pressure in the pressure sensor had increased to over 400 kPa and the floc recycle pump shut off. The team quickly loosened the clamp and decreased the pressure to 280 kPa. Finally, the pressure stabilized at 320 kPa.

3.2.8 Summary of Design Parameters

Important design parameters that were calculated in previous sections are shown below in table 2.

Table 2: Summary of design parameters

Parameter	Symbol	PACl dose	Value
PACl stock concentration	$C_{CoagStock}$		1 g/L
PACl flow rate	$Q_{CoagStock}$	5 mg/L	0.0027, 0.0032, 0.0040, 0.0048, 0.0055 mL/s
		10 mg/L	0.0054, 0.0065, 0.0081, 0.0097, 0.011 mL/s
		20 mg/L	0.011, 0.013, 0.016, 0.019, 0.022 mL/s
PACl dose	C_{Plant}		5, 10, 20 mg/L
Plant flow rate	Q_{Plant}		0.54, 0.65, 0.81, 0.97, 1.1 mL/s
Upflow velocity	v_{SedUp}		1, 1.2, 1.5, 1.8, 2 mm/s
Head loss	H		1 m
Diameter of hydraulic jet	d_{Jet}		0.39 mm
Velocity gradient for a coiled flocculator	G_{Coiled}		40. s^{-1}
Hydraulic residence time	θ		$1.4 \times 10^3\ s$
Capture velocity	$V_{Capture}$		0.11 mm/s
Recycle ratio	$\Pi_{Recycle}$		0.10
Recycle flow rate	Q_R		0.054, 0.065, 0.081, 0.097, 0.11 mL/s
Plant flow rate with floc recycle	$Q_{NewPlant}$		0.49, 0.58, 0.73, 0.87, 0.99 mL/s

3.3 Process Controller Method Files

Our team used process controller to control and record data for our experiments. Each experiment has a process controller method file that is saved in a file on the AguaClara server under Research>Floc Sed Optimization>Data Processor>Experiments>X-XX-201X. The last name in the file path is the date the experiment was conducted. The process controller method file is updated and renamed every time a new experiment is run; the name indicates the major differences between experiments such as a difference in coagulant dose or upflow velocity.

The figure below8 is an example of the states used in process controller to run our experiment. The first state under the list, OFF, is in use when the entire plant is turned off. OFF indicates no pumps are running, no clay is being dosed and therefore no data is being recorded. State 1, entitled 1. 100 NTU 0 FRR 10mgperL is used to build and floc blanket with 100 NTU water and 10mg/L of PACL. The States tab indicates which pumps and valves are off and on in each state. In this method file, Pump 0 corresponds to all actions of the raw water pump, Pump 2 corresponds to the floc recycle and Pump 5 controls the coagulant dosing.

State 2. Floc Recycle is the state used to implement floc recycle into the plant. State 2. Floc Recycle includes all of the same set points used in State 1, the main difference is that in State 2, Pump 2 will be on, recycling flocs into the plant.

The states entitled Calibrate pump 0.80 and Calibrate pump 0.05 are not used in our every day experiments. Both of these states are used when the peristaltic pumps (0, 2 and 5) need to be calibrated. Calibrate pump 0.80 will turn on the pump to 80% of the pumps possible flow rate and calibration can occur from there is the flow rate the pump is reading is not actually 80%. Similarly, Calibrate pump 0.05 goes to the other extreme and will turn on the flow rate at 5% of the possible pump flow rate and from there calibration can occur.

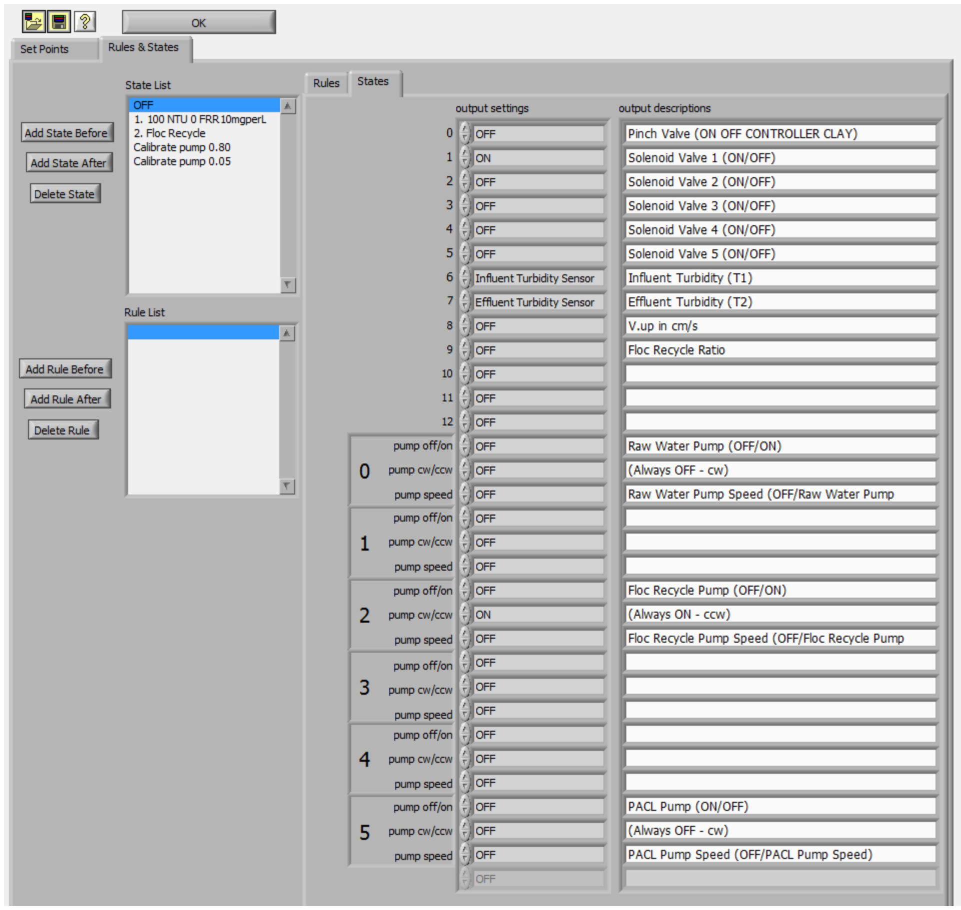

Figure 8: Process Controller Rules and States

The below figure 9describes the plant operation. This is where states can be manually or automatically implemented. The two choices under Mode of Operation include “Manual Locked in State” and “Automatic Operation”. Currently the method file uses Manual Locked in State. When the team needs to change from State 1 to State 2 (turn on floc recycle), it is necessary to come in a switch the state manually under the tab Operator Selected State. The options under the Operator Selected State tab include all of the states mentioned previously.

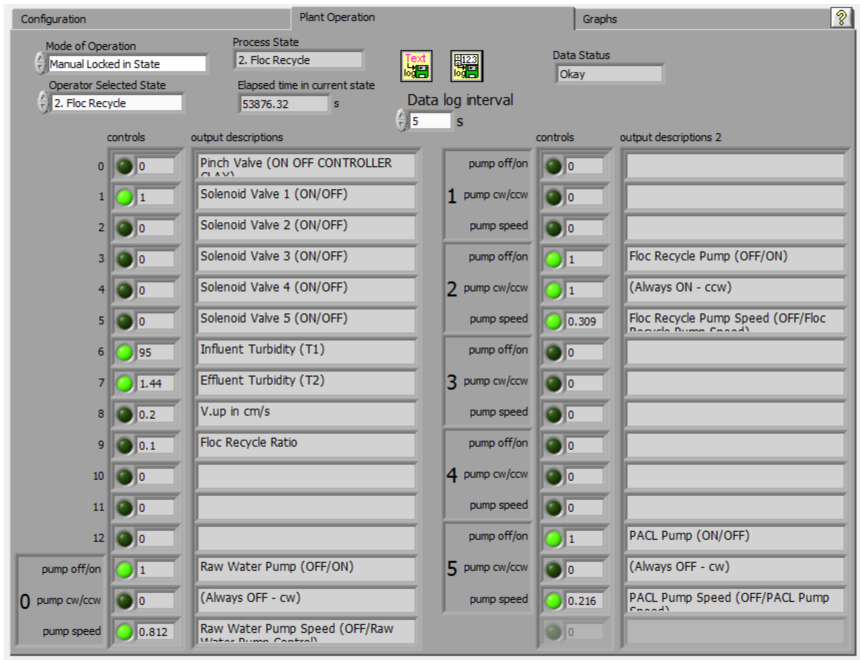

Figure 9: Process Controller Plant Operations

The table3 below displays the set points in one state of the process controller method file as can be seen by the figure below the table 10. Constants are shown in gray rows, and variables are shown without color. These set points are the same in both State 1 and State 2, however between the two states constant values have changed. Each state will use the set points listed to control the plants pumps and chemical dosing. The up flow velocity in the sedimentation tank changes for each experiment.

Table 3: Set Point Descriptions

Set Point	Value	Required Set Points	Function	Purpose
OFF	0			Set point for plant when nothing is running
1. Pinch Valve ON TIME	110 ms			Controls how long the clay pinch valve is open and dumping clay
1. Pinch Valve OFF TIME	8 s			Controls how long the clay pinch valve is closed

Set Point	Value	Required Set Points	Function	Purpose
ON	1			Set point for when plant is operating (manual or automatic)
1. Pinch Valve OnDuty ON		Pinch Valve ON TIME, PINCH VALVE OFF TIME, ON	Math\duty cycle	Regulates the cycle of the pinch valve turning on and off
1. Raw Water Min Target	95 NTU			Gives the influent turbidimeter a minimum target to maintain; if the turbidimeter reads below this, the clay valve opens
1. Raw Water Max Target	105 NTU			Gives the influent turbidimeter a maximum target to maintain; if the turbidimeter reads belows this, the clay valve stays shut
T1 ID	1			Where the influent turbidimeter is located
Influent Turbidity Sensor (T1)		T1 ID	HF turbidimeter\HF turbidimeter (com1).vi	Reads and records data from influent turbidimeter
1. ON OFF CONTROLLER CLAY		OFF, Pinch Valve OnDuty ON, Raw Water Min Target, Raw Water Max Target, Influent Turbidity Sensor (T1)	math\on-off controller setpoint sensor1.vi	
T2 ID	2			Where the effluent turbidimeter is located

Set Point	Value	Required Set Points	Function	Purpose
Effluent Turbidity Sensor (T2)		T2 ID	HF turbidimeter\HF turbidimeter (com1).vi	Reads and records data from effluent turbidimeter
1. Raw Water Control		1. Plant Flow Rate, Tubing size 16	peristaltic\peristaltic pump (mLpers).vi	Control the flow rate of the raw water pump
2. Raw Water Control w Recycle		2. Plant Flow Rate w Recycle, Tubing Size 16	peristaltic\peristaltic pump (mLpers).vi	Controls the flow of the raw water pump when floc recycle is running
2. Plant Flow Rate w Recycle		2. Plant Flow Rate w Recycle, 2. Floc Recycle Control	math\subtract.vi	Controls the entire plant flow rate when floc recycle is running
1. Plant Flow Rate		1. Area, Sed Tank, 1, V.up	math\multiply.vi	Calculates the plant flow rate based in the desired up flow velocity in the sedimentation tank.
1. PACL Pump Control		1. Plant Flow Rate, 1. PACl Stock Concentration, 1. PACl Dose, Tubing size 13	chem dose pumps\chem dose pump (mLpers).vi	Controls the flow rate of the PACl coagulant pump
2. Floc Recycle Ratio	100 m			Provides the ratio for the calculation of the flow rate in the floc recycle line
2. Floc Recycle Control		2. Floc Recycle Flow Rate, Tubing Size 14	peristaltic\peristaltic pump (mLpers).vi	controls the rate of the floc recycle pump
2. Floc Recycle Flow Rate		1. Plant Flow Rate, 2. Floc Recycle Ratio	math\multiply.vi	calculates the flow rate through the floc recycle line, used in the calculation

Set Point	Value	Required Set Points	Function	Purpose
1. Area, Sed Tank	5.41cm^2 cm^2			Provides the area dimension of the sedimentation tank to be used in flow calculations
1. V.up	1, 1.2, 1.5, 1.8, 2.0 mm/s			Up flow velocity in the sedimentation tank, used in the plant flow rate calculation (varies depending on experiment)
1. PACL Stock Concentration	1000 mg/L			Value of the coagulant stock concentration pumped into the plant
1. PACL Dose	5, 10, 20 mg/L			Desired concentration of coagulant entering the plant (varies depending on experiment)
1. Time for 100 NTU Start-up	20.9061 ks			A time value used in automatic operation to switch between states. Current value of 20.906ks is one solids residence time in the plant
Floc Interface			camera\Camera Floc Interface.vi	Connects process controller to camera using the settings created in camera configure byto calculate recording the height of the floc-water interface
Calibrate Pump 0.05	50 m			
Calibrate 0.80	800 m			
tube size 13	13			Value of tubing size 13, used in PACl pump control calculations

Set Point	Value	Required Set Points	Function	Purpose
tubing size 16	16			Value of tubing size 14, used in floc recycle pump control calculations
tubing size 14	14			Value of tubing size 16, used in Raw water pump control calculations
2. Time for Floc Recycle	14.4 k			A time value used for the length the state 2 with floc recycle pumps on should run
Floc Height	75 cm			A height value that can be used to switch between state 1 and state 2 when the floc blanket is detected by the camera at value indicated
Recycle Pump on/off Control		off value, on value, min target, max target	feedback control\on-off controller.vi	This set point can be used to turn and off the floc recycle pump when the floc blanket height is measured at a critical value in camera configure

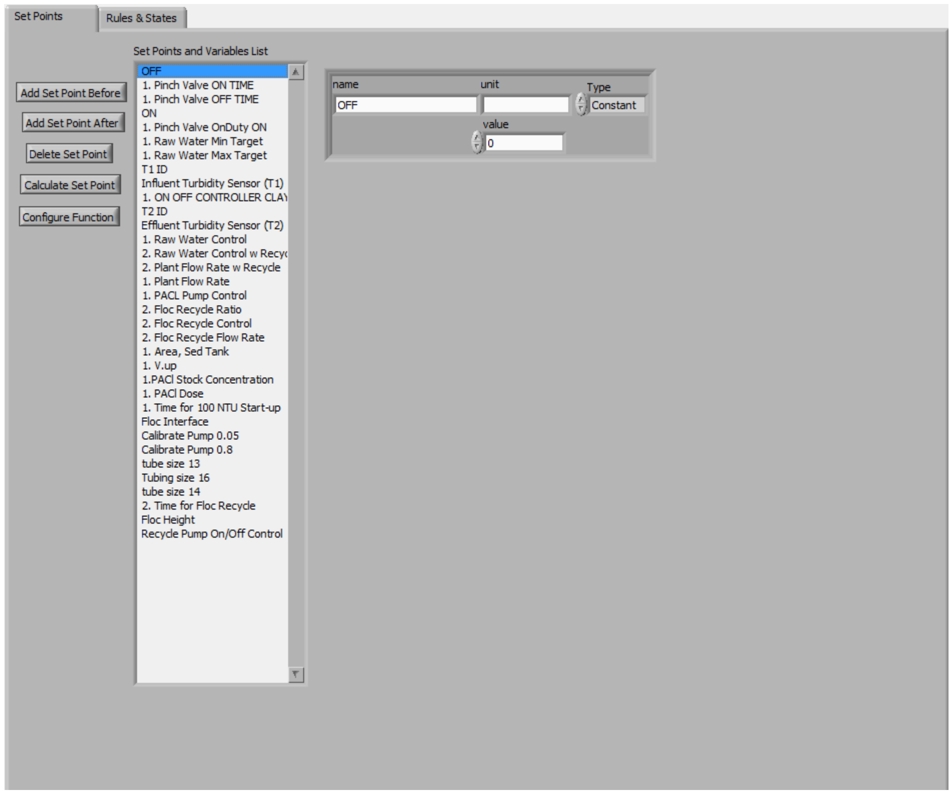

Figure 10: Process Controller Method File

3.3.1 Clay Dose Adjustment

Influent turbidity data in early experiments was showing that clay was not being properly dosed into the system. Influent measurements were increasing to over 200 NTU every time the clay pinch valve was opened, while the intended turbidity was 100 NTU. The team increased the time the clay pinch valve was off from 5 seconds to 10 seconds and decreased the time the pinch valve was on from 1 second to 0.11 seconds to regulate the clay dose less often and in smaller amounts. The tubing connecting the clay bucket to the pinch valve was replaced and shortened to ensure there was no slack in the tubing. This would keep clay from accumulating in low points and clog the tubing.

4 Experiments and Analyses

The testing parameters are listed in table 4 below.

Table 4: Testing parameters

Parameter	Symbol	Values
PACl dose	C_{Plant}	5 mg/L
		10 mg/L
		20 mg/L
Upflow velocity	v_{SedUp}	1 mm/s
		1.2 mm/s
		1.5 mm/s
		1.8 mm/s
		2.0 mm/s
Influent turbidity		100 NTU

These parameters were tested in the order in table 5.

Table 5: Order of Experiments

Experiment number	PACl dose	V_{Up}	Recycle ratio	Camera
1	10 mg/L	1 mm/s	0	No
2	10 mg/L	1 mm/s	0	No
3	10 mg/L	1 mm/s	0	No
4	10 mg/L	1 mm/s	0	No
5	10 mg/L	1 mm/s	0	No
6	10 mg/L	1 mm/s	0	No
7	10 mg/L	1 mm/s	0	Yes
8	5 mg/L	1.2 mm/s	0.10	Yes
9	5 mg/L	1.2 mm/s	0.10	Yes
10	20 mg/L	1.2 mm/s	0.10	Yes
11	10 mg/L	1.2 mm/s	0.10	Yes
12	5 mg/L	1.2 mm/s	0.10	Yes
13	5 mg/L	1.2 mm/s	0	Yes
14	20 mg/L	1.2 mm/s	0	Yes
15	20 mg/L	1.5 mm/s	0.10	Yes
16	20 mg/L	2.0 mm/s	0.10	Yes
17	5 mg/L	1.8 mm/s	0.10	Yes
18	10 mg/L	2.0 mm/s	0.10	Yes

This semester the team ran experiments with three different coagulant doses: 5 mg/L, 10 mg/L and 20 mg/L of PACl all at an influent turbidity of 100 NTU. The influent and effluent turbidities were graphed in Mathcad as well as the pC* graphs for the first state as well as a combined graph of the influent and effluent turbidities and pC* in the first and second states (built a full floc blanket in the first state and incorporated floc recycle in the second state). Videos of an experiment at each PACl dose can be found on the AguaClara YouTube site.

The team first experimented with 10 mg/L of PACl without floc recycle.

The upflow velocity of the plant was set at 1.00 mm/s. The effluent turbidity for these experiments were generally very low, ranging between 0.5 and 2 NTU. However, the floc blanket would often collapse into a solid bed, as show in figure 11 after a few hours so the team decided that it may be because the upflow velocity was too low so it was changed to 1.20 mm/s.

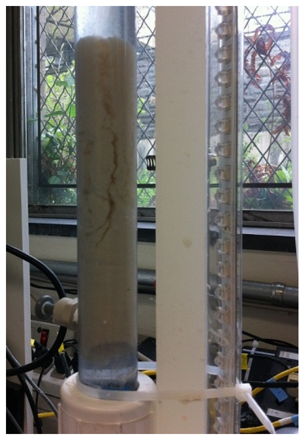

Figure 11: Collapsed Floc Blanket

In the experimental data shown below, the PACl dose was 10 mg/L for 100 NTU. The upflow velocity was 1.2 mm/s and the floc recycle ratio was at 10% of the upflow velocity. There was no clamp present in this experiment. Figure 12 shows the effluent turbidity and Figure 13 shows the pC* graph of the experiment from April 25th.

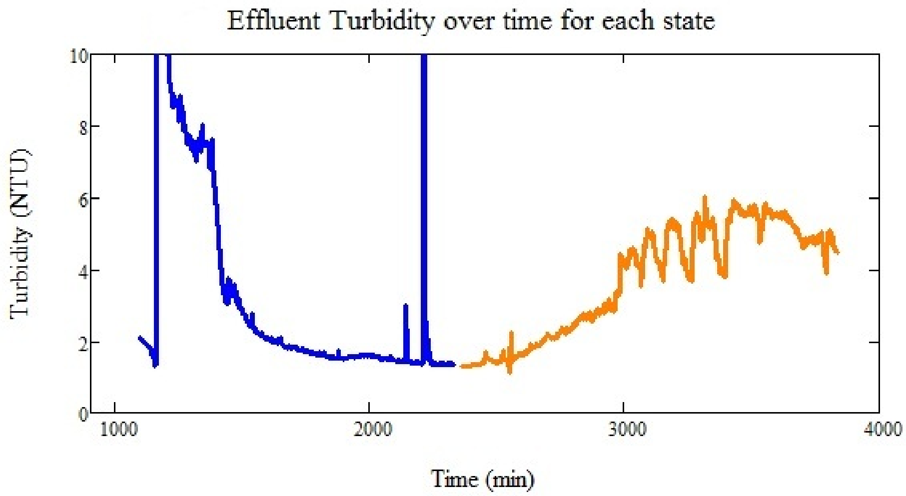

Figure 12: Effluent Turbidity with 10 mg/L PACl

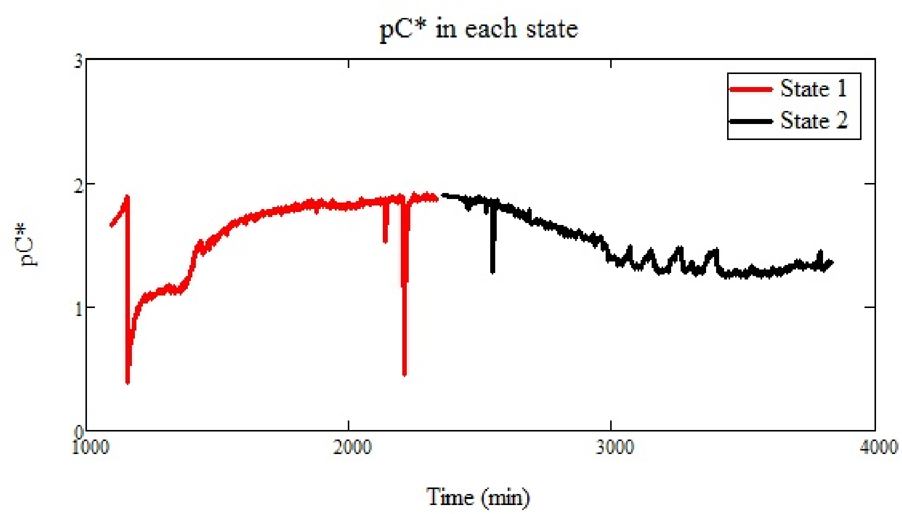

Figure 13: pC* Graph for 10 mg/L PACl experiment

Influent turbidity stayed at about 100 NTU for the entire experiment and that the effluent turbidity decreased until the team started floc recycle. Floc recycle did not seem to work since the effluent turbidity increased slightly from about 1.5 NTU to about 5 NTU and the pC* value decreased. .

Floc blanket height measurements were also made during the experiments, and the experiment done on April 16 to 17th with 10 mg/L of PACl and 1.2 mm/s of upflow velocity was one of the successful height measurements made by Camera Configure. The smoothing length was set to 1.5 and minimum derivative was set to 0.5.The measurements are shown in figure 14 below.

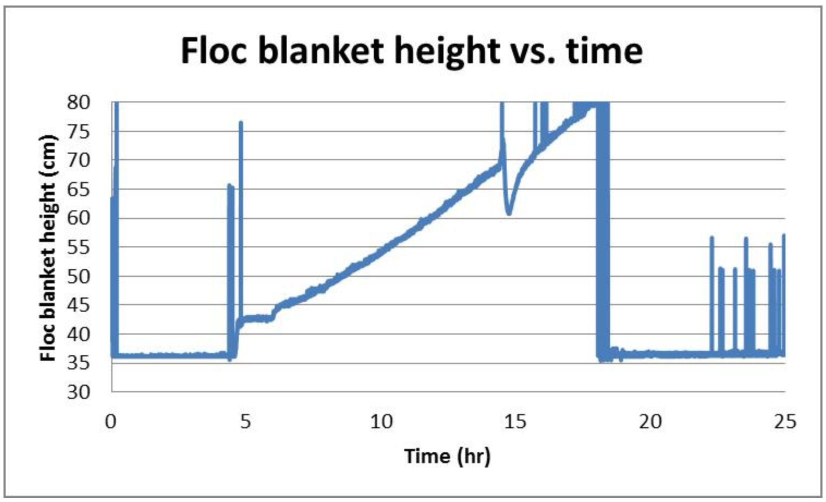

Figure 14: Floc blanket height measurements for the experiment on April 16 to 17th with PACl of 10 mg/L and upflow velocity of 1.2 mm/s

This experiment ran for approximately one day. First, when there was no floc blanket in the sedimentation tank, the height was at approximately 36 cm, or at the bottom of the sedimentation tank. The camera started to detect floc blanket building up five hours after the experiment started. The floc blanket built up in a linear fashion until 18 hours after the experiment started. Then, the floc blanket height dropped to 36 cm again, which shows that the sedimentation tank was full with floc blanket and the camera could not detect a floc-water interface anymore. Floc recycle started shortly after the floc blanket was fully built, and no floc-water interface was detected at these times as well. This shows that floc recycle did not affect the floc blanket to settle or to flush out.

The team then ran experiments using 5 mg/L PACl with influent turbidity at 100 NTU, 1.2 mm/s upflow velocity, 10% floc recycle ratio and no clamp. For these experiments, the floc blanket took a much longer time to build (almost 24 hours), and therefore each experiment ran over the course of 2 or 3 days. The graphs effluent turbidity are shown in Figure 15 and the pC* graph are shown in Figure 16 for the experiment from April 21st.

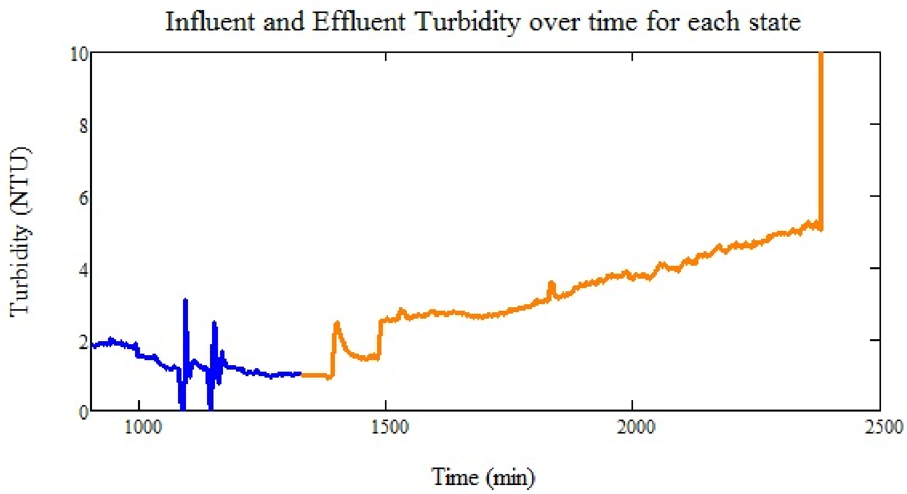

Figure 15: Effluent Turbidity with 5 mg/L PACl

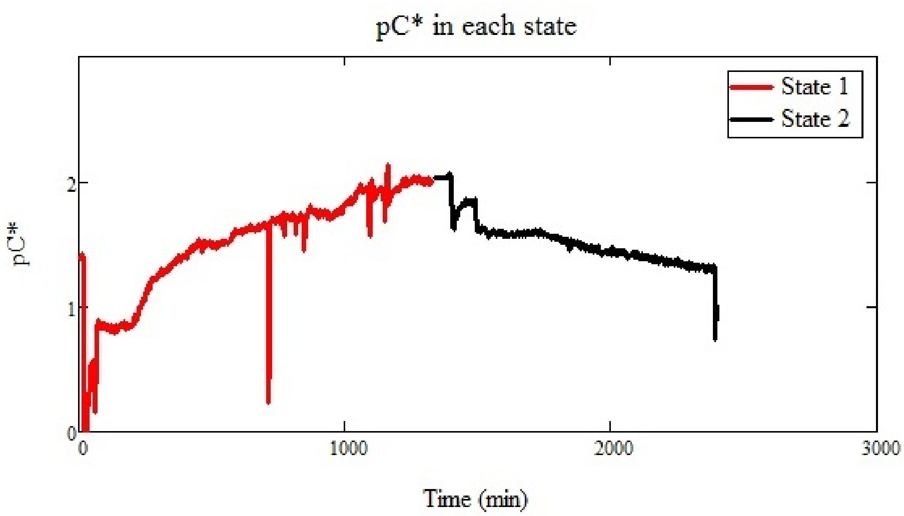

Figure 16: pC* for 5 mg/L PACl experiment. Floc recycle bega at ??? s

This experiment had very similar results to the experiment from April 25th. The effluent turbidity decreased steadily over the first half of the experiment where the floc blanket was being built. The pC* also increases steadily during this time. However, like the 10 mg/L experiment, the effluent turbidity increased when floc recycle was added and the pC* value decreased steadily.

The team also ran experiments using 20 mg/L PACl with all other parameters unchanged. The floc blanket again collapsed in many of these experiments so the team increased the upflow velocity to 1.50 mm/s. However, the floc blanket still collapsed. The team then increased it again to 2.00 mm/s. The team predicted that the flocs were too large which caused the floc blanket to collapse. To try and resolve this problem, the team added a clamp to the floc recycle line as shown in figure 7.

A graph of the turbidities and pC* of a 20 mg/L experiment from April 22nd are shown in Figure 17. The clamp was not yet added to the apparatus at this point, but it also appears that floc recycle did not work because the effluent turbidity increased when floc recycle was started. Furthermore, the pC* value began to decrease when floc recycle was started as shown in figure 18.

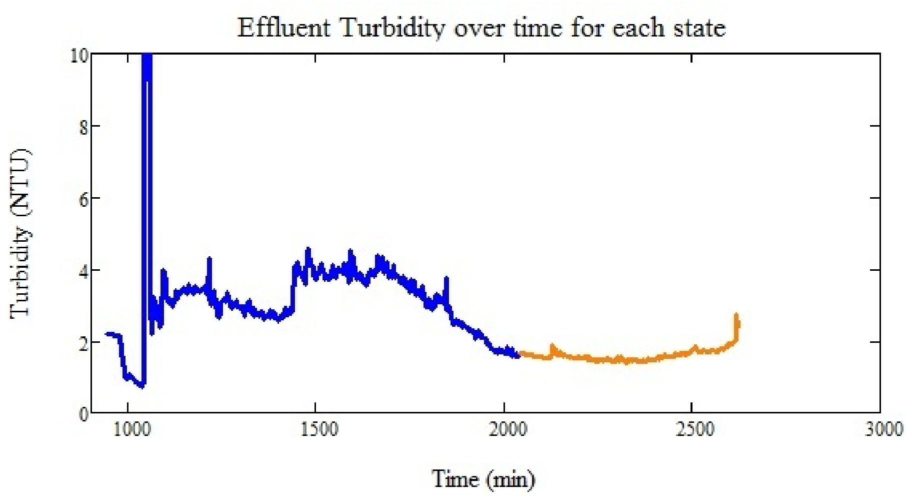

Figure 17: Influent and Effluent Turbidities with 20 mg/L PACl. Floc recycle began at ?? s.

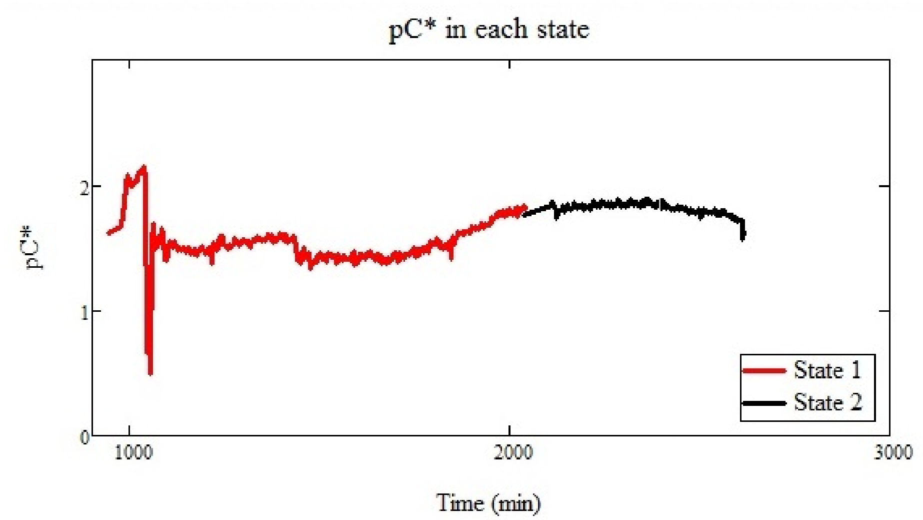

Figure 18: pC* Graph for 20 mg/L PACl experiment

The team performed two experiments with the clamp on the floc recycle line. Figure 1919 shows the effluent turbidity for an experiment with 5 mg/L PACl dose, at an influent turbidity of 100 NTU, an upflow velocity of 1.8 mm/s, and a recycle ratio of 10%. The graph of effluent turbidity in Figure 20 19below show that even with the addition of the clamp, the effluent turbidity increased when floc recycle started and the pC* decreased as well, as shown in Figure 2120.

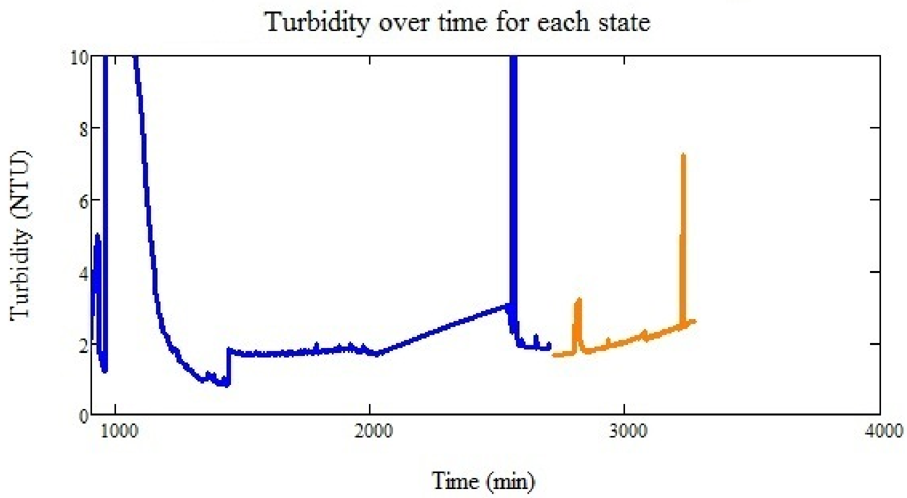

Figure 19: Effluent Trubidity for 5 mg/L PACl experiment with clamp

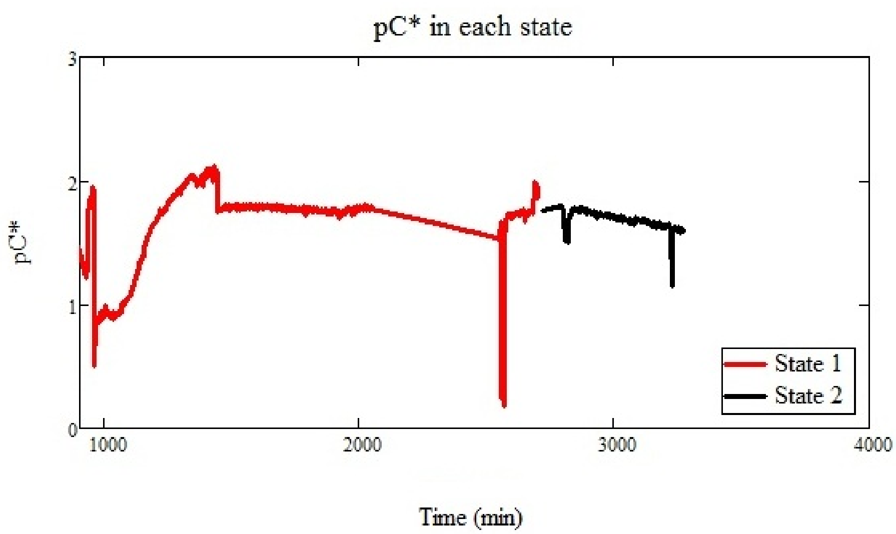

Figure 20: pC* for 5 mg/L PACl experiment with clamp

The team also performed an experiment with 20 mg/L PACl dose, 100 NTU influent turbidity, an upflow velocity of 2.0 mm/s, recycle ratio of 10% and a clamp on the recycle line. This experiment yielded similar results to all the others where the effluent turbidity increased when floc recycle was started. The pC* value also decreased when floc recycle was started which is what happened in all of the previous experiments. The effluent turbidity was higher with the 20 mg/L PACl dose experiment than with the 5 mg/L PACl one, which shows that the higher the PACl dose does not make the effluent turbidity lower.

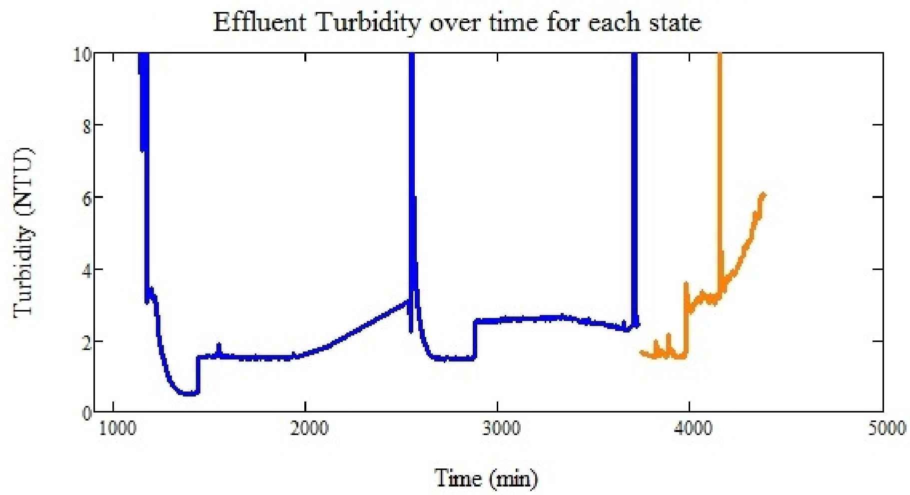

Figure 21: Effluent Turbidity for 20 mg/L PACl experiment with clamp

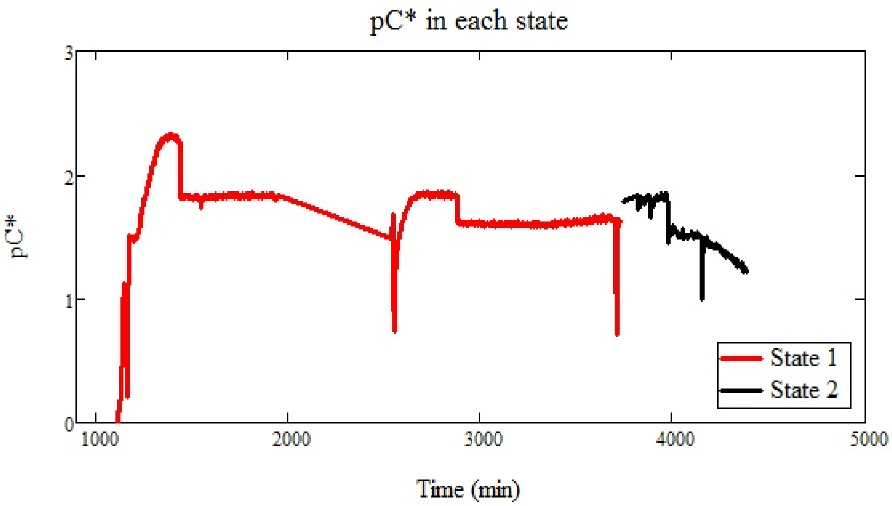

Figure 22: pC* for 20 mg/L PACl experiment with clamp

The team found that floc recycle was not helpful. The effluent turbidities increased after floc recycle was started. The team thought that this could be because the flocs were too large and could not attach to any new clay particles. On the other hand, the flocs could be too small because it was being run through a preastaltic pump which would break up the flocs and just add extra dirt particles and increase the influent turbidity.

In addition, fluctuation of flow rate produced by the raw water pump was observed for some experiments. This can be explained by the increase in upflow velocity because the plant flow rate increased and was set to above 80 rpm. Since 80 rpm was the upper value used for calibration of pumps, the pump could not deliver the proper flow rate set in Process Controller. The maximum observed raw water pump flow rate was approximately 89 rpm when the proper flow rate was 81.1 rpm. When this flow rate was observed, it was also observed that water leaked from the top valve as discussed in section 3.1.3. It was hypothesized that the sudden increase in the raw water flow rate also caused the leak in addition to what was discussed in section 3.1.3.

Floc blanket concentrations of the above three experiments (experiments 16, 17, and 18) without floc recycle were measured by taking 5 mL samples from the middle of the sedimentation tank, diluting them to 100 mL, and measuring the turbidities. This procedure was repeated for three times for each dose to ensure more accurate measurements. Results are shown below in table 6. PACl dose of 10 mg/L had the least turbidity and that of 20 mg/L had the greatest turbidity. These floc blanket concentration measurements were not consistent with the effluent turbidity results since 20 mg/L experiment had the greatest measured turbidity and 5 mg/L experiment did not show an extreme turbidity.

Since effluent turbidity measurements were lower with 5 mg/L dose than with 20 mg/L dose, it was expected that the lower dose would result in higher floc blanket concentration. There would be smaller flocs with lower dose, so with a larger surface area, more clay can be removed, which would lead to a more concentrated floc blanket and lower effluent turbidity.

Possible reasons why the floc blanket concentrations were not consistent with the effluent turbidity measurements are human error and the state of the floc blanket when measured. The experiment was running when the measurements were taken, and flocs may not had been equally distributed in the sedimentation tank.

Table 6: Floc blanket concentrations

Experiment	PACl dose	Measured turbidity
16	20 mg/L	3.8×10^3 NTU
17	5 mg/L	3.3×10^3 NTU
18	10 mg/L	2.3×10^3 NTU

5 Conclusion

Overall, the team found that floc recycle was not effective at any of the three tested coagulant doses since it made the effluent turbidity higher. The pC* values when full floc blankets formed were approximately the same in all 3 cases. Before floc recycle began, the pC* increased for the 5 mg/L experiment and decreased then increased for the 20 mg/L experiment. At 10 mg/L the pC* value increased until floc recycle was started. After floc recycle began pC* decreased. Overall for all the experiments that the team ran this semester, yielded similar results. After floc recycle was started, the effluent turbidity increased and the pC* value decreased. Therefore, the team does not recommend that floc recycle be incorporated into AguaClara plants.

6 Future Work

The team will continue to work on back lighting the sedimentation tank and finding the optimal placement for the webcam and the best way to connect the LED strip to the sedimentation tank. Currently the side of the LED strip is still sticking out of the side of the sedimentation tank because it is too long for the tank. We will also continue to work on configuring the camera so that it will be able to detect the height of the floc blanket and the floc blanket concentration. The team will also determine whether a diffuser, such as low density polyethylene, for the LED strip would help the camera detect the floc blanket. The best way to determine floc concentration has not been determined yet, but we have considered taking a sample from the floc blanket, diluting it by a known amount and then measuring the turbidity.

The team will continue to experiment with varying coagulant doses and floc recycle. The team has only experimented with coagulant doses of 5 mg/L and 10 mg/L.

The team still had issues with the clay particles getting stuck to the side of the tubing in the flocculator which is what the rapid mix chamber was supposed to solve. Also the mold growing in the sedimentation tank could be what making the camera interface jump around. While it is better than it was last semester, the team is in the process of cleaning out the flocculator and sedimentation tank with diluted bleach and water.

The team will also determine a new way to connect the LED lights and diffuser to the sedimentation tank because it is not a very stable apparatus and a lot of the time it shifts and the camera will not pick up the floc blanket or it will jump between different parts of the sedimentation tank. However, an alternative method to attaching the LED strip and diffuser have not been decided yet and will be discussed with Paul next week.

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