Flocculator and Sedimentation Tank Optimization

Marion Alberty, Ju Khuan Pan, Kester Wilkening

May 11th, 2012

1 Introduction

Currently AguaClara plants do a satisfactory job of delivering clean water to communities, and there has been a lot of research into how to optimize each individual process within AguaClara plants. However, there is a need to optimize the plants as a whole in order to reduce construction and operating costs. This has become especially important since the addition of the stacked rapid sand filter. With the filter, the target turbidity from the sedimentation tank effluent can be increased, i.e. the water can be incrementally dirtier coming out of the sedimentation tank. This could mean two of the largest processes within AguaClara plants, flocculation and sedimentation, may be over-designed. If the size of either of these two systems can be reduced, AguaClara plants could become even more affordable. This will increase the availability of AguaClara plants to communities in need of effective water treatment technologies.

The goal of our research is to optimize the overall effectiveness of AguaClara plants by focusing on flocculation and sedimentation. This will be done by observing the effects of varying the different parameters that control the design of each process. In the Spring 2012 semester, an optimal sedimentation tank upflow velocity, V_{SedUp} , was determined to be 2mm/s. Some important insights about implementing floc recycle were also obtained. The next parameters to be studied are detailed in the Future Work section of this paper.

2 Literature Review

2.1 Coagulant

In the masters' thesis presented by Matt Hurst [3], optimal alum dosages were studied for 10, 100, 200 and 500 NTU raw water. For raw water with a turbidity of 100 NTU, the variability of turbidity in the tube settlers significantly decreased as alum dosages were increased from 25 mg/L to 45 mg/L. Optimal dosages of alum for 100 and 200 NTU raw water were noted to be 45 mg/L and 65 mg/L, respectively. It was also noted that performance did not deteriorate at higher dosages of alum in either case. Testing for optimal alum dosages was also done for raw water of 10 and 500 NTU. Using the four data points acquired, the following empirical relationship for optimal alum dosages was attained:

$$Alum_{Dosage}(mg/L) = 7.8(Turbidity)^{0.4} \tag{1}$$

This could be a conservative estimate, in particular for 500 NTU water, nevertheless it will be used as the initial coagulant dose in the system. As with other portions of the water clarification process, the coagulant dosage in the system will be examined and possibly changed.

2.2 Rapid Mix and Flocculation

The velocity gradient (G) in the rapid mix system is a key parameter to determine how well the influent water and coagulant (alum) are mixed. The velocity gradient is a measure of how the layers of fluid move at different speeds across the cross section of the rapid mix tubing. These differential speeds cause shear forces that mix the raw water and alum, such that the suspended solids in the water are coated with alum. These "sticky" particles can then collide to form bigger flocs in the flocculator. The calculation of G is defined under the "Methods" section of this paper, and the desired value of G will determine the dimensions of the rapid mix. The desired value for G in rapid mix is 500 s^{-1}, as determined by the jar test performed by Dan Smith [6].

Ian Tse, et. al (2011)[7], discusses the relationship between G inside a laminar flow flocculator and collision potential. The value of G determines the dimensions of the flocculator similar to the process for designing the rapid mix unit. However, the optimal G for flocculation is much smaller, ranging from 30 to 100 s^{-1}. Below 30 s^{-1}, there is insufficient mixing to provide collisions . Above 100 s^{-1}, the velocity gradient is so large that it starts to break up larger flocs. The goal of flocculation is to have flocs that are large enough so that they are able to settle out before leaving the sedimentation tank.

Residence time, θ, is the amount of time in seconds the particles are in the flocculator. Collision potential is a measure of the ability of the laminar flow reactor to produce collisions, and it is described by:

$$CollisionPotential(unitless) = G(\theta) \tag{2}$$

Residence time is largely dependent on the length of the flocculator. One of the goals of this research is to reduce the residence time of the flocculator, which will reduce the size of the actual flocculators in AguaClara plants. Since the apparatus in this experiment will be optimizing the residence time, it is important that the velocity gradient be within the desired range. In actual AguaClara plants the flocculators are turbulent, so in that case energy dissipation is used to determine the overall flocculation potential. However, for lab purposes, laminar flow allows the use of G to determine flocculator dimensions.

2.3 Sedimentation Tank

The final report of the AguaClara Sedimentation Tank Hydraulics Team[2] reported that a mixture of raw water and clay with a turbidity of 100 NTU and a coagulant dosage of $45mg/L\,Alum$ can form a floc blanket. However, according to Matt Hurst[3], when influent turbidity is reduced (<5 NTU) the floc blanket is eventually washed out. For the experiments presented in the thesis, raw water turbidity ranged from 10 to 500 NTU. Improved performance was found to correlate with the height of the floc blanket. However, tube settlers were necessary to achieve an effluent turbidity of less than 1 NTU. The optimum floc blanket height can be interpreted as being 45 cm, as floc blanket performance did not appear to improve beyond that height in cases where tube flocculation was present. Previous AguaClara research has shown that at the inflow of the sedimentation tank, a conical geometry is best to re-suspend settling flocs that are drawn down and can be propelled upwards by the inflow jet[1].

2.4 Tube Settlers

Angled tube settlers are a compact way to remove low NTU water from the top of the sedimentation tank. It has been shown in current AguaClara plants that an angle of 60^o is an optimal design for angled tube settlers. The angled tubing decreases the distance flocs have to fall to hit the side of the tubing. Since the velocity at the wall of the tube settler is very low, the flocs can then roll down the side of the tube settlers and back into the sedimentation tank.

The Final Report from the AguaClara Floc Roll-up Tube Settlers Team[4] analyzes the phenomena of floc roll-up. They found that this failure is caused by high velocity gradients in the tube settlers, which arise from either too small of a tube diameter or too high of an upflow velocity causing floc particles to travel up the tube settlers. These failure points have been taken into consideration and are detailed under the Methods section.

2.5 Floc Recycle

In [5], McLane, John C. details the success of a floc recycle system in treating raw water with a wide ranging turbidity (4 to 3000 NTU) at a water treatment plant in Fort Madison. A submersible sump pump was installed at the bottom of the settling tank, to extract settled sludge and reintroduce it back into the plant just before rapid mix. Over a period of 7 years, the recycle system proved to be extremely successful at improving the water quality of the finished water. Regardless of the incoming turbidity, turbidity of the effluent from the sedimentation basin has stabilized at about 3.0 NTU, a 90% reduction from the values of 30 to 50 NTU achieved previously. Heterotrophic plate counts, a test for bacteria, were also reduced from >100,000/mL to < 10/mL in the sedimentation basin effluent. The success of floc recycle in this water treatment plant is the inspiration behind the incorporation of floc recycle into the team's research this semester.

3 Methods

3.1 Plant Schematic

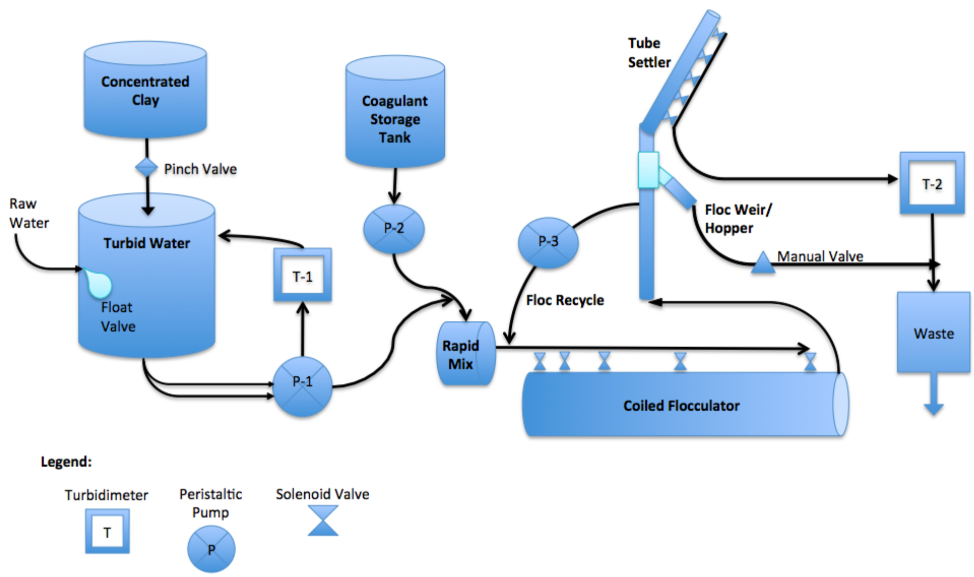

Figure 1: Plant Schematic

The team created a detailed plant schematic to aid in the design calculations for our experiments. The design was based on the previous setup that was present in the laboratory and the suggestions given in the team's challenge document. This enabled the group to easily organize the results from calculations of tube size, sedimentation tank diameter, flocculator coil diameter and tube settler outflow locations on the schematic in a manner that was easily understandable and user friendly. The simplified version presented above only depicts the planned experimental setup without dimensions and design decisions.

The physical experimental setup is presented in the following figures.

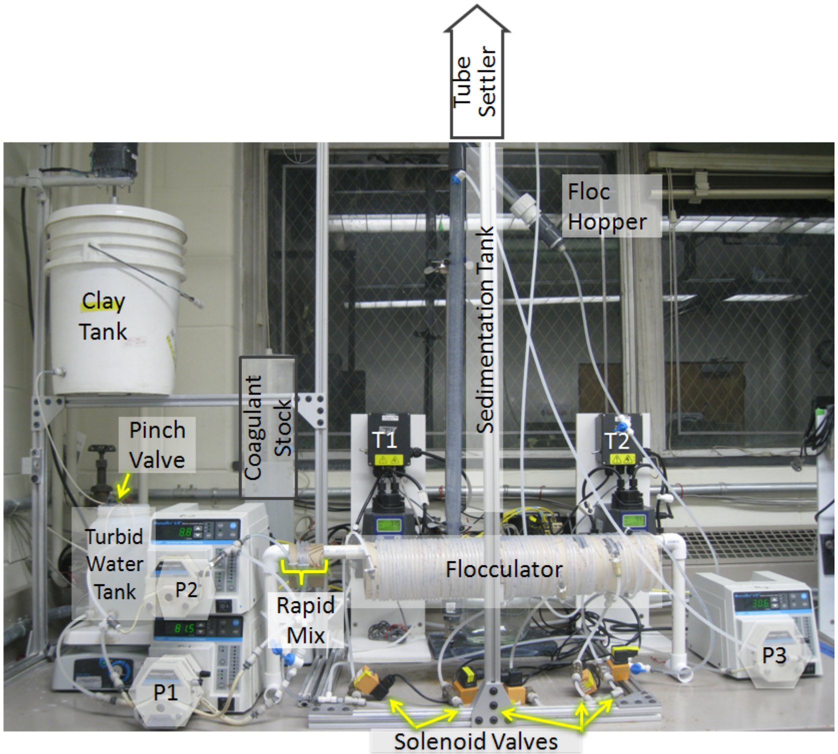

Figure 2: Experimental Setup (Front view)

Figure 3: Experimental Setup (Side view)

3.1.1 Floc Hopper Design

The floc hopper controls the height of the floc blanket in the sedimentation tank, and also allows time for the floc blanket overflow to consolidate and dewater. For experimental purposes, a floc hopper was created by placing a wye connection above the desired height of the floc blanket (See Figure 4). A compression fitting is used to connect the pipe to tubing, and the outflow from the wye is controlled by a manual valve. The floc blanket flows over the wye and flocs settle down to the manual valve. During 3 NTU operation, the manual valve is closed, causing the flocs to consolidate within the miniature floc hopper. The outlet valve is opened periodically in order to waste the dewatered flocs. This process mimics the actual cleaning process that would occur for a full scale floc hopper in an AguaClara plant.

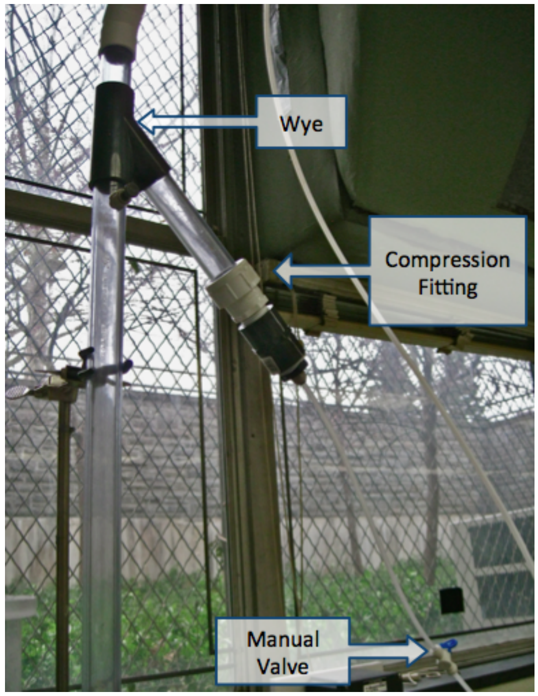

Figure 4: Floc Hopper

3.1.2 Floc Recycle Design

The floc recycle line allows a limited amount of flocs from the floc blanket to be pumped back into the beginning of the flocculator. The floc recycle line draws flocs from just below the top of the floc blanket. It was determined that the density of the flocs within the floc blanket is uniform enough that flocs can be pulled out at any height within the floc blanket, and this should not decrease the effectiveness of the floc recycle.

Once the floc-water mixture is in the floc recycle line, it was observed that flocs may begin to settle out onto the walls of the line. To prevent this settling from occurring, the velocity in the tubing must be high enough to overcome the settling velocity of the flocs. The velocity in the tubing is affected by the tube diameter of the floc recycle line, plant flow rate, and floc recycle ratio.

The floc recycle system then reintroduces the turbid water back into the main system just after the rapid mix and before the flocculator. It is thought that inserting recycled flocs at this point will provide the newly mixed, "sticky" particles with more suspended solids to "stick" onto and form flocs. Floc recycling is expected to increase the floc solids concentration in the flocculator and thus, increase collision potential within the flocculator. As a result, it is likely that the length of the flocculator or coagulant dose could be decreased when floc recycle is implemented.

3.1.3 Elevated Waste Line

The waste line was elevated above the source of the raw water in order to increase the total head of the water moving through the experimental set up. The additional elevation head translates to an increase of pressure in the flocculator. This increase of pressure prevents dissolved gases from escaping out of solution and creating bubbles within the set-up. At the highest point of the waste line, an aeration tube was also added to allow any air trapped within the line to escape to the atmosphere (See Figure 5).

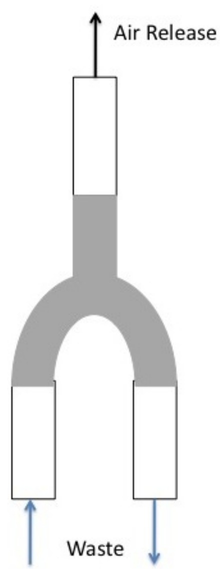

Figure 5: Elevated Waste Line Schematic

3.2 Design Decisions

A MathCAD file was used to calculate the operating parameters and dimensions required for the experimental setup.

The team's objective is to test the range of parameters listed in Table 1 while meeting the constraints established by the literature review.

Table 1: Range of parameters to test

Parameter	Symbol	Method	Parameter Range
Flocculator length	L_{Floc}	5 solenoid valves to select the inlet location	1 m, 2 m, 5 m, 10 m, 20 m
Sedimentation upflow velocity	V_{SedUp}	vary the flow rate through the entire plant with maximum collision potential and capture velocities	$1\,\frac{mm}{s}$, $1.5\,\frac{mm}{s}$, $2\,\frac{mm}{s}$, $2.5\,\frac{mm}{s}$
Ratio of upflow to capture velocity	$\Pi_{Capture} = \frac{V_{Capture}}{V_{SedUp}}$	5 solenoid valves to select the outlet location from tube settler	0.05, 0.1, 0.15, 0.2, 0.25
Recycle flow rate ratio	$\Pi_{Q_{Recycle}} = \frac{Q_{Recycle}}{Q_{Plant}}$	variable speed peristaltic pump on recycle line	0, 0.02, 0.05, 0.1, 0.2
Raw water turbidity		pinch valve based on measured turbidity	$3\,NTU$, $500\,NTU$

3.2.1 Sedimentation Tank

The lab-scale sedimentation tank is a vertical, clear pipe. Its inner diameter, $D_{SedTank}$, and the upflow velocity, V_{SedUp} determine the total plant flow rate, Q_{Plant}.

The inflow from the flocculator into the sedimentation tank has to be delivered by a pipe with a minimum diameter, $D_{FlocToSedMin}$, calculated using Equation3.

$$D_{FlocToSedMin} = \left(\frac{Q_{Plant}}{\varepsilon_{Max}^{\frac{1}{3}}} \frac{4\Pi_{Jet}}{\pi} \right)^{\frac{3}{7}} \tag{3}$$

The value of ε_{Max}= 10 $\frac{mW}{kg}$ andΠ_{Jet} = 0.4 used in AguaClara plants is also assumed here. The jet from the pipe will be discharged at the bottom of a cone to facilitate the formation of a floc blanket.

The tube settler is a clear PVC pipe connected to the top of the sedimentation tank at 60 degrees to the horizontal. It has the same inner diameter as the sedimentation tank, so $D_{TubeSettler} = D_{SedTank}$. Instead of varying the absolute value of capture velocity, the $\frac{V_{SedUp}}{V_{Capture}}$ ratio will be changed.

In order to achieve the desired $\frac{V_{SedUp}}{V_{Capture}}$ ratio, the length of the tube settler is calculated according to Equation 4. There will be multiple outflow locations along the tube settler, controlled by solenoid valves.

$$L_{TubeSettler} = \frac{D_{TubeSettler}\left(\frac{V_{TubeUp}}{V_{Capture}} - 1\right)}{\cos\alpha_{TubeSettler} * \sin\alpha_{TubeSettler}} \tag{4}$$

where$\alpha_{TubeSettler} = \frac{\pi}{3}$ is the angle of the tube settler to the horizontal and V_{TubeUp} is the vertical velocity component in the tube settler.

To check that $D_{TubeSettler}$ and Q_{Plant} will not cause floc roll-up, Equation5 was used, which is derived in[8].

$$D_{TubeSettler} \geq \frac{3V_{TubeUp}d_{Floc}}{V_{Capture}\sin^2\alpha_{TubeSettler}} \tag{5}$$

$$d_{Floc} = d_0 * \left(\frac{18V_{Capture}\Phi\nu_{H2O}}{gd_0^2}\frac{\rho_{H2O}}{\rho_{Floc,0} - \rho_{H2O}}\right)^{\frac{1}{D_{Fractal}-1}} \tag{6}$$

where d_{Floc} is the diameter of a floc with a sedimentation velocity equal to the capture velocity, $d_0 = 1\,\mu m$ is the primary particle diameter (clay and coagulant), $\Phi = \frac{45}{24}$ is a shape factor for drag on flocs, $\rho_{Floc,0}$ is the density of primary floc particles, $D_{Fractal}$ is 2.3.

3.2.2 Flocculator

The flocculator must have a velocity gradient between 30 to 100/s. The average G in laminar tube flow is defined by Equation 7for a straight tube, where Q is the volumetric flow rate and r is the inner radius of the tube.

$$G_{Straight} = \frac{8Q}{3\pi r^3} \tag{7}$$

For a coiled flocculator, the method outlined by Tse et. al.[7] is used to calculate G:

$$G_{Coiled} = G_{Straight}(1 + 0.033(\log(De))^4)^{\frac{1}{2}} \tag{8}$$

Where $De = \frac{VD}{\nu}\left(\frac{D}{2D_{Coil}}\right)^{\frac{1}{2}}$is the Dean number, D is the inner diameter of the tube, D_{Coil} is the diameter of curvature, and υ is the kinematic viscosity of the fluid.

The inner diameter of the tube flocculator, D_{Floc}, and the diameter of the coil, $D_{FlocCoil}$, was varied in order to achieve G_{Coiled} of within $30s^{-1}$ to $100s^{-1}$.

3.2.3 Rapid Mix

There will be a pump to deliver coagulant from the coagulant stock tank. This flow rate, $Q_{CoagStock}$, will determine the dosage. Hence, the appropriate flow rate of the pump will depend on the turbidity of the raw water and the total plant flow (See Equation 9).

$$Q_{CoagStock} = \frac{Q_{Plant} C_{CoagDose}}{C_{CoagStock}} \tag{9}$$

Where $C_{CoagDose}$ is the desired coagulant dose, and $C_{CoagStock}$ is the concentration of coagulant in the coagulant stock tank.

Using the empirical formula (See Equation 1) developed by Hurst (2009)[3], $C_{CoagDose}$ is approximately $15mg/L$ for 3 NTU water and $95mg/L$ for 500 NTU water.

The rapid mix system is a coiled tube. To achieve good mixing, the desired G in the rapid mix coil is $500s^{-1}$. Equations 7 and 8 apply here as well. The inner diameter of the rapid mix tubing, D_{RapMix} and the diameter of the coil, $D_{RapMixCoil}$, were varied in order to achieve the desired range of G. However, the team decided to relax the constraints on G and use a tubing size that was more readily available instead.

Another constraint for the rapid mix system is that the point of mixing between the raw water and coagulant should occur at most 1 *second* away from the rapid mix coil, in order to reduce the opportunity for the coagulant to precipitate on itself. This can easily be ensured by minimizing the length of tubing between the point of mixing and the coil.

3.2.4 Summary of Design Decisions

Tables 2 and 3 summarize the design decisions we have made for the first iteration of our experiments.

Table 2: Summary of Dimensions

Parameter	Symbol	Values
Inner Diameter of Pipe into Sedimentation Tank	$D_{FlocToSedMin}$	$\frac{3}{16}in$
Inner Diameter of Sedimentation Tank	$D_{SedTank}$	$1.033in$
Inner Diameter of Tube Settler	$D_{TubeSettler}$	$1.033in$
Location of Tube Settler Outlet	$L_{TubeSettler}$	$0.989m, 0.464m, 0.289m, 0.202m, 0.149m$
Inner Diameter of Flocculator	D_{Floc}	$\frac{3}{16}in$
Diameter of Flocculator Coil	$D_{FlocCoil}$	$12cm$
Inner Diameter of Rapid Mix	D_{RapMix}	$\frac{1}{8}in$
Diameter of Rapid Mix Coil	$D_{RapMixCoil}$	$9cm$
Concentration in Coagulant Stock Tank	$C_{CoagStock}$	$2g/L$
Coagulant Dose for 3 NTU water	$C_{CoagDose}$	$15mg/L$
Coagulant Dose for 200 NTU water		$65mg/L$
Coagulant Dose for 500 NTU water		$95mg/L$
Tubing from Coagulant Stock Tank to Rapid Mix Coil	$L_{Stock2RapMix}$	$0.17in$
Inner Diameter of Floc Recycle Line	$D_{FlocRecycleLine}$	$\frac{1}{8}in$

Table 3: Summary of Operating Conditions

Turbidity (NTU)	$V_{SedUp}(\frac{mm}{s})$	$Q_{Plant}(\frac{mL}{s})$
3	1	0.541
	1.5	0.811
	2	1.081
	2.3	1.352
500	1	0.541
	1.5	0.811
	2	1.081
	2.3	1.352

3.2.5 Converting Desired Flow Rates to Pump Speeds

Table 4shows the flow rates that can be achieved by a peristaltic pump for different tubing sizes. It can be used to calculate the equivalent pump speeds (rpm) for desired flow rates.

Table 4: Pump Speeds corresponding to different tube sizes and flow rates (Peristaltic Pumps)

Tubing Number	13	14	16	17	18
Max Pump Speed (rpm)	100	100	100	100	100
Max Flow Rate (mL/min)	6.0	21.0	80.0	280	380

Given a tubing number, this relationship can be used to find the corresponding pump speed:

$$RPM_{Tubing} = \frac{Q_{Desired}}{Q_{Tubing,Max}} * RPM_{Tubing,Max} \tag{10}$$

Where the subscript "Tubing" indicates that the values of the parameters correspond to the selected tubing size. Table 5 shows the sizes of the peristaltic pump tubing used for the three pumps in the experimental set up.

Table 5: Peristaltic Pump Tubing Sizes in the Experimental Set Up

Pump Number	Purpose of Pump	Peristaltic Pump Tubing Size
1	To deliver raw water into the plant	16
1	To deliver water into the influent turbidimeter	17
2	To deliver coagulant into the rapid mix system	13
3	To recycle flocs	14

3.3 Order of Experiments

Table 6details the proposed order in which the team planned to vary each parameter for this semester. Each test should be done at both 500 and 3 NTU in order to test the upper and lower limits of expected influent turbidities in an AguaClara plant. The tests will be paired with another of the same turbidity so that there is less transition time between tests. During the 3 NTU tests, a floc blanket will first be built at 200 NTU. The system will then transition into a 3 NTU state before continuing with the rest of the experiment.

The first column in the table below describes the proceeding order of experiments. Once an optimal variable is found, that variable will be used throughout the rest of the experiments.

Table 6: Proposed Order of Experiments

Goals	L_{Floc}	V_{SedUp}	$\Pi_{Capture}$	$\Pi_{Q_{Recycle}}$	Turbidity
Test System, Build Floc Blanket	20 m	1 mm/s	0.1	0	200 NTU
Maintain Floc Blanket	20 m	1 mm/s	0.1	0	3 NTU
Maintain Floc Blanket	20 m	2 mm/s	0.1	0	3 NTU
Optimal Floc Recycle Ratio	20 m	2 mm/s	0.1	vary	3 NTU
Optimal Floc Recycle Ratio	20 m	2 mm/s	0.1	vary	500 NTU
Min Flocculator Length, maintain floc blanket	vary	2 mm/s	0.1	optimal	500 NTU
Min Flocculator Length, maintain floc blanket	vary	2 mm/s	0.1	optimal	3 NTU
Max/Optimal Upflow Velocity	minimum	vary	0.1	optimal	3 NTU
Max/Optimal Upflow Velocity	minimum	vary	0.1	optimal	500 NTU
Max/Optimal Capture Velocity Ratio	minimum	optimal	optimal	optimal	500 NTU
Max/Optimal Capture Velocity Ratio	minimum	optimal	vary	optimal	3 NTU
Optimal Coagulant dose	minimum	optimal	optimal	0	3 NTU
Optimal Coagulant dose	minimum	optimal	optimal	optimal	3 NTU
Optimal Coagulant dose	minimum	optimal	optimal	0	500 NTU
Optimal Coagulant dose	minimum	optimal	optimal	optimal	500 NTU

3.4 Process Controller

Process Controller software was used to automate the experimentation process. Process Controller controls the pumps and solenoid valves, and collects data from the turbidimeters at 5-second intervals.

Each experiment was coded as a process controller method file, broken down into separate, independent "states". Each state keeps the system running under a different set of conditions. Boolean expressions in the form of "rules" are then used to switch between the states.

To illustrate, three states will be required in order to run the system at both 200 and 3 NTU: one to run it at 200 NTU, one for the transition between the two turbidities, and one to run it at 3 NTU. A rule for maximum elapsed time would control the duration of the first and last states, while a rule for the value of the influent turbidity would govern the duration of the transition state.

3.5 Data Processing

MathCAD is used to process the experimental data that is collected by Process Controller. Functions are used to extract the run time, influent and effluent turbidity data from the Process Controller data log. The extracted data is then smoothed by taking the average of every 10 data points.

There are two ways to visualize the results of each experiment: the user can specify one particular state to analyze, or choose to analyze all states within an experiment. The resulting array of smoothed values will be plotted over the duration of each state if the user desires to view only the data from one selected state. For the user who prefers to see data from the entire experiment, a single averaged turbidity value will be calculated for each state and plotted against the state number. The user will be able to specify the particular time interval within each state for which to average the turbidity values. The team has decided to average the turbidity values that occurred 0.5 to 2 hours after the beginning of each state. Since all states run for at least 2 hours, the system should probably have settled into a steady state during that interval. Both methods of data analysis will be presented in the team's results and discussion.

MathCAD is also used to compute performance statistics such as the $pC*$ during a particular state. $pC*$ is a measure of turbidity removal efficiency that is independent of influent turbidity, and is calculated using the following equation:

$$pC* = -\log\left(\frac{EffluentTurbidity}{InfluentTurbidity}\right) \tag{11}$$

4 Results and Discussion

4.1 Building and Maintaining a Floc Blanket

Several experiments were performed to test the system's ability to build and maintain a floc blanket at various values for V_{SedUp}. Good performance (<3 NTU effluent turbidity) was observed throughout the the experiment where V_{SedUp} was 2 mm/s (See Figure 6). In the first state where the floc blanket was built with an influent turbidity of 200 NTU, effluent turbidity underwent minor fluctuations in the first hour before the floc blanket had begun to build up (See Figure 7). At approximately 2.5 hours into this state, effluent turbidity approached a steady-state value below 1 NTU. This time scale seemed to correspond with the floc blanket reaching the floc hopper. In the third state, the floc blanket was maintained at an influent turbidity of 3 NTU. A trend of increasing effluent turbidity is apparent over the duration of approximately 4 hours, but effluent turbidity was consistently below 1 NTU (See Figures 9). pC* also remained quite steady for the duration of the third state at about 0.6 (See Figure 10). An image of the top of the floc blanket at the end of the experiment is shown in Figure 11.

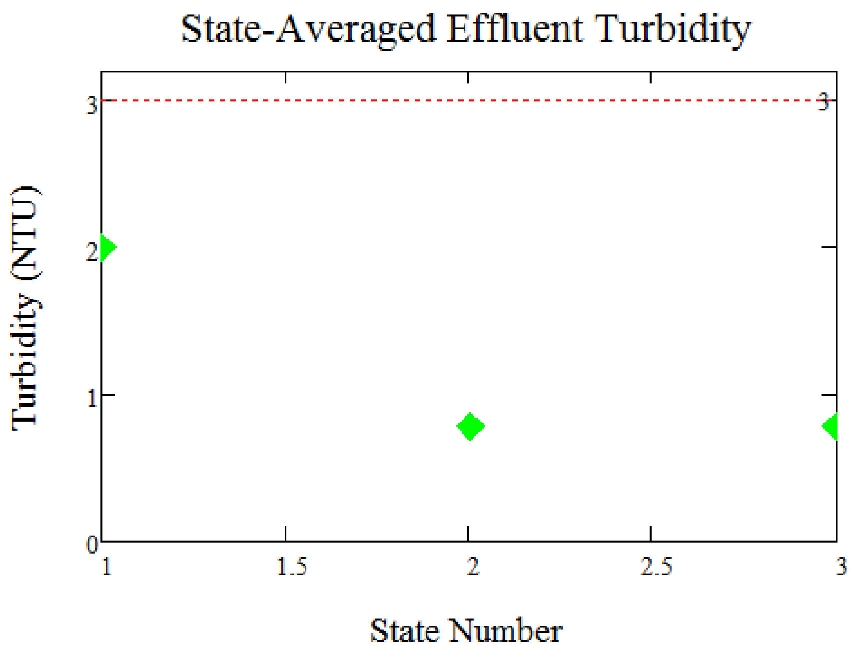

Figure 6: State-Averaged Effluent Turbidity when V_{SedUp} is 2 mm/s. The red dotted line indicates the 3 NTU threshold.

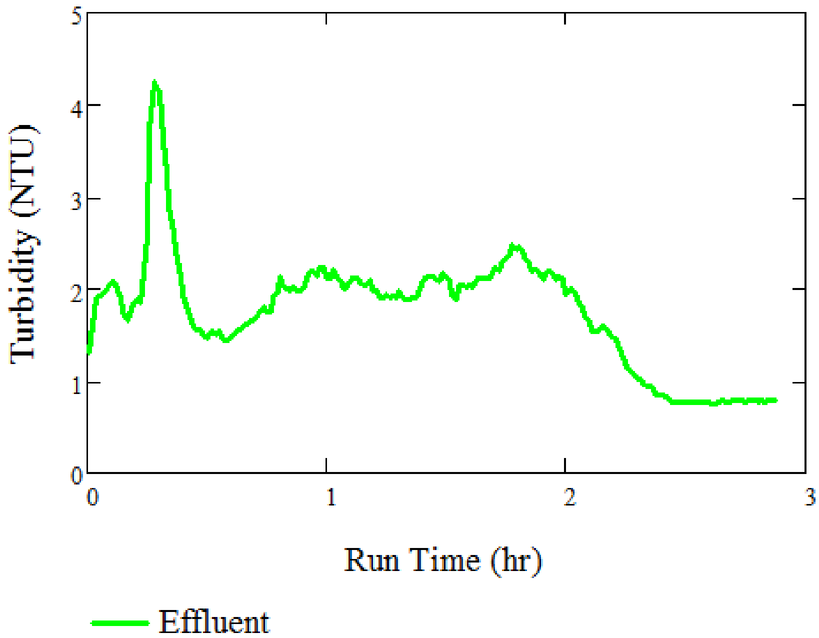

Figure 7: Effluent Turbidity in 500 NTU Building State (State 1)

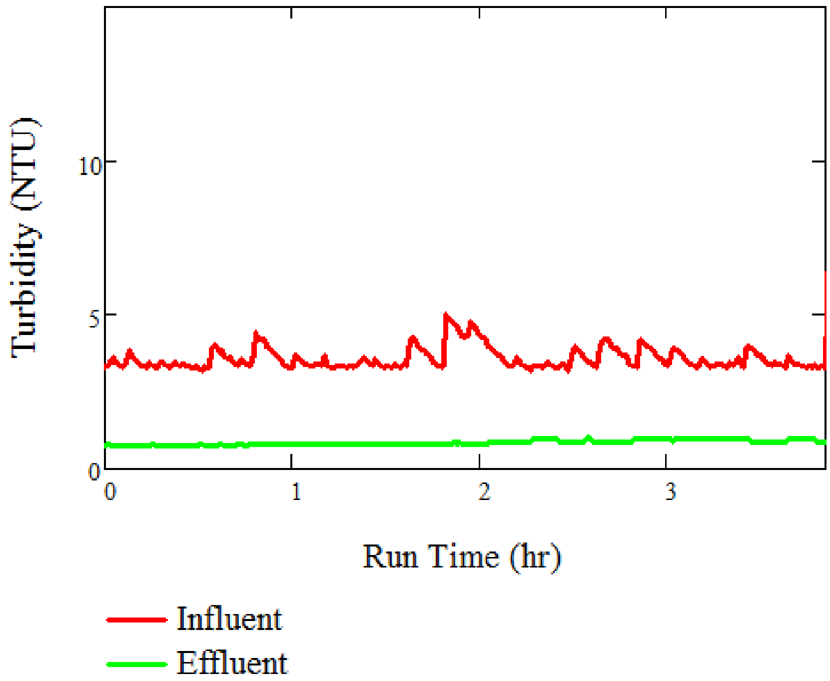

Figure 8: Influent & Effluent Turbidity in 3 NTU Maintenance State (State 3)

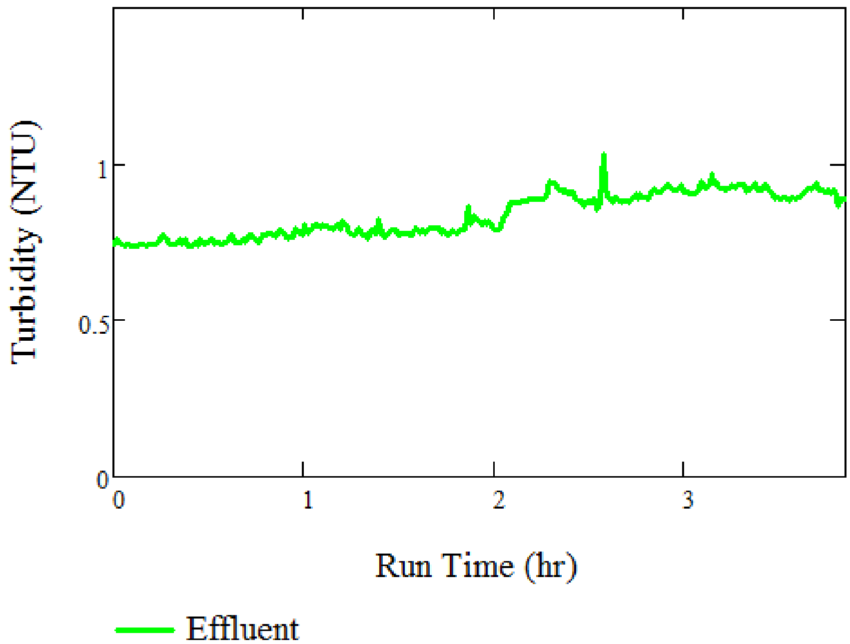

Figure 9: Effluent Turbidity in 3 NTU Maintenance State (State 3)

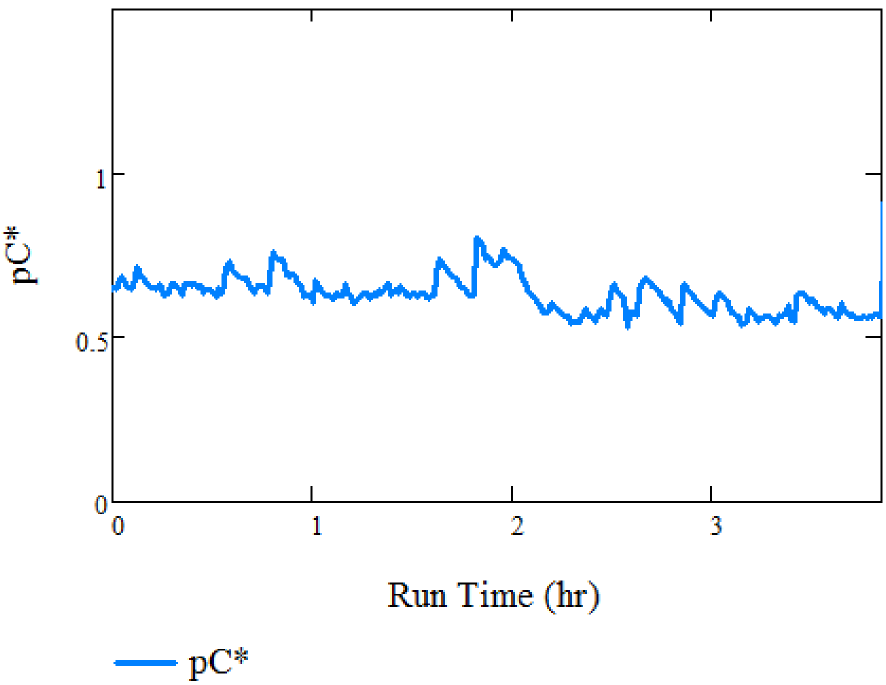

Figure 10: pC* in 3 NTU Maintenance State (State 3)

Figure 11: Top of Floc Blanket at the end of 3 NTU Maintenance State (State 3)

The same experiment was repeated with V_{SedUp} incremented to 2.25 mm/s. A floc blanket was built and maintained, but effluent turbidity could not be maintained below 3 NTU throughout the experiment (See Figure 12). This indicated that a V_{SedUp} of 2.25 mm/s was too high, and that optimizations of other parameters should probably proceed with a V_{SedUp} of 2 mm/s or a value between 2 to 2.25 mm/s.

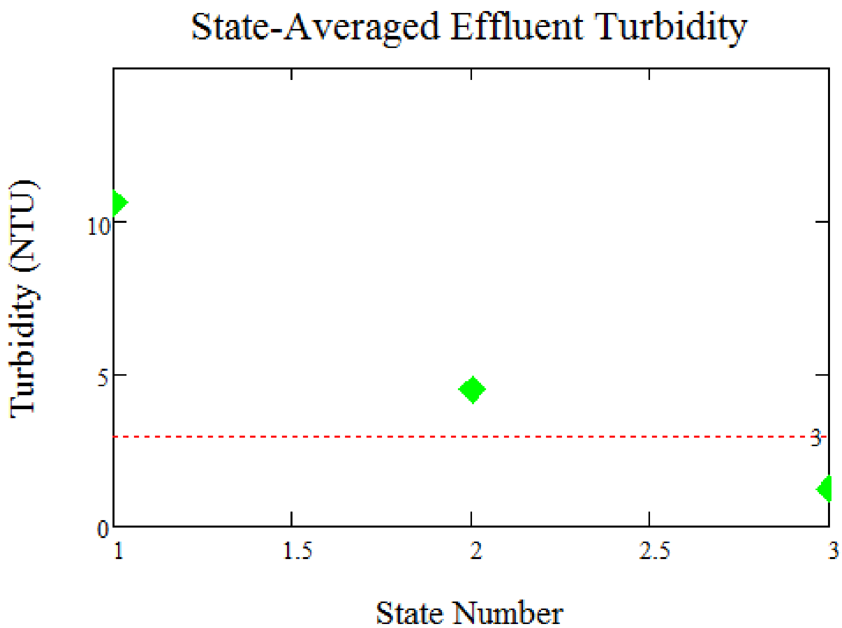

Figure 12: State-Averaged Effluent Turbidity when V_{SedUp} is 2.25 mm/s. The red dotted line indicates the 3 NTU threshold.

4.2 Experimental Observations

4.2.1 Flocculator Length Observations

It has been noticed that in experimental states where the influent turbidity was approximately 200 NTU or of comparable magnitude, that the flocs in the flocculator do not seem to increase in size after traveling half the length of the flocculator. From these observations, it appears that experiments of altering flocculator length could be very fruitful. However, similar observations have not been made for the flocs in the flocculator during states where influent turbidity was approximately 3 NTU or of comparable magnitude. At these states it is difficult to visually detect flocs in the flocculator, nonetheless track their size over the length of the flocculator.

4.2.2 Floc Recycle Observations

An experiment was preformed where a $\Pi_{Q_{Recycle}}$ of 0.1 was tested after maintaining a floc blanket at a V_{SedUp} of 2 mm/s and influent turbidity of 3 NTU for 4 hours. Approximately 5 minutes prior to the beginning of floc recycle, the top of the floc blanket was quite sparse (See Figure 13). However about 23 minutes later, after the start of floc recycle, the top of the floc blanket had become quite dense again (See Figure 14). A possible reason for this observation is that floc recycle could have resulted in more flocs forming in the flocculator and entering the sedimentation tank to build a denser floc blanket. It is important to note that while Q_{Plant} was maintained at 1.081 mL/s for the entirety of the experiment, during states where floc recycle was implemented, the velocity in the part of the sedimentation tank within the floc recycle loop increased to 2.2 mm/s, or the product of $1 + \Pi_{Q_{Recycle}}$ and V_{SedUp}. This is because floc recycle increases the flow rate and thus the velocity of the water within the loop where floc-water mixture is circulated. This increase in V_{SedUp} did not appear to negatively effect the floc blanket or effluent turbidity at this Q_{Plant}, but should be considered when designing further experiments.

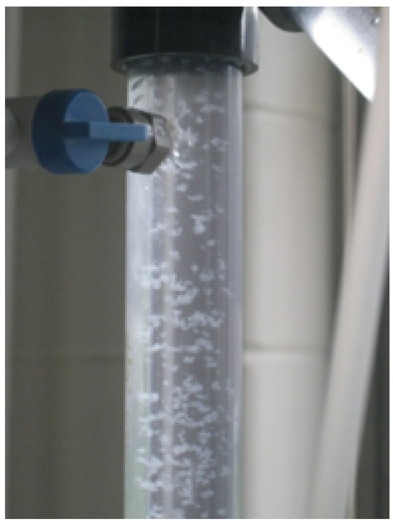

Figure 13: The Top of the Floc Blanket 5 min. Prior to the Beginning of Floc Recycle

Figure 14: The Top of the Floc Blanket 18 min. After the Beginning of Floc Recycle

4.3 Decreasing Coagulant Dosage with Floc Recycle

The addition of floc recycle has the potential to streamline two aspects of AguaClara plant design: flocculator length and coagulant dose. Since coagulant makes up a significant percentage of the AguaClara plant operating costs, the team chose to explore this parameter before ending the semester. The design of this experiment was primarily driven by the following question: can coagulant dose be reduced when floc recycle is implemented, while still achieving $<$ 3 NTU effluent? The team decided to proceed with a floc recycle ratio of 0.1, as this ratio did not seem to hinder floc blanket maintenance at a V_{SedUp} of 2 mm/s. However, since floc recycle has the greatest impact when more flocs are recycled and the floc blanket is denser at a lower V_{SedUp} , the team ran this experiment at 1.5 mm/s instead of 2 mm/s. As suggested by our instructor, Dr. Weber-Shirk, an estimate of the target coagulant dose was calculated by assuming linearity between the optimal dose at 200 and 3 NTU influent turbidity using Equation 12. However, the equation was altered to reflect the limitations of the physical set-up, while still minimizing coagulant dose at the 3 NTU state (Equation 13).

$$C_{CoagDose,3NTU} = \frac{3}{200} * C_{CoagDose,200NTU} \qquad (12)$$

$$C_{CoagDose,3NTU} = \frac{7}{130} * C_{CoagDose,200NTU} \qquad (13)$$

Effluent turbidity data obtained from this experiment proved unreliable due to system errors. However, qualitative observations obtained from this experiment provided some insights. For example, lowering the coagulant dose at 3 NTU might cause the floc blanket to thin out. Pictures of the top of the floc blanket at 3 NTU and varying coagulant dosages are presented in Figure 15.

In addition, it was observed that flocculator performance improved when floc recycle was implemented with a thick floc blanket. At a coagulant dose of 15 mg/L, a sample of flocculated water obtained from the system had a measured turbidity of 105 NTU. Given that the raw water turbidity was 3 NTU, this showed that floc recycle from a thick blanket was indeed increasing the suspended solids concentration within the flocculator. Visual observations of the flocculator corroborated this finding. Figure 16 shows visible flocs within the flocculator when floc recycle was implemented at 3 NTU with a coagulant dose of 15 mg/L. Previously, flocs were not visible in the flocculator at 3 NTU. However, as the coagulant dose decreased, the floc blanket thinned, and the effect of floc recycle on increasing the flocculator turbidity seemed to decrease as well, as can be seen in Figure 17. However, the team definitely recommends repeating this experiment to confirm the validity of the aforementioned observations.

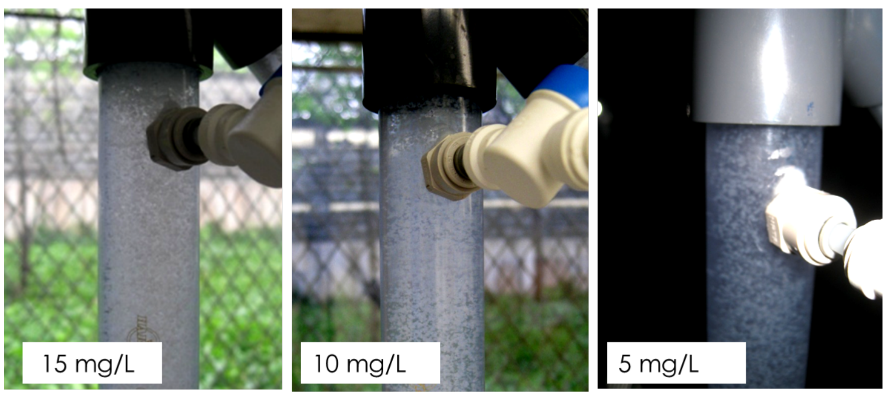

Figure 15: Floc Blanket maintained with 3 NTU influent and varying coagulant dosages

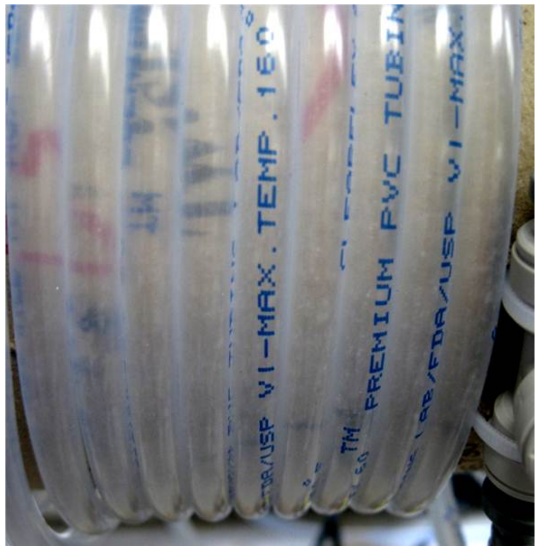

Figure 16: Visible flocs forming in the flocculator in the 3 NTU state with floc recycle ratio of 0.1

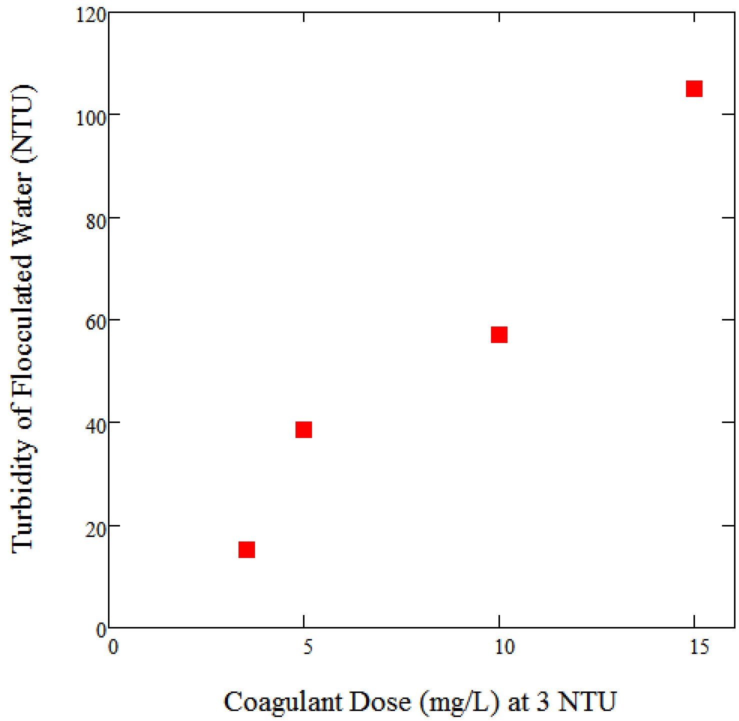

Figure 17: Turbidity of Flocculated Water (NTU) against Coagulant Dose (mg/L) for 3 NTU raw water

5 Conclusions

The team has spent the most of this semester preparing a solid foundation for future optimization research. Multiple experimental failures have spurred the team to make continuous improvements to the system design, and the result is a neat, relatively robust experimental system that should provide the next team with a good starting point for future optimization experiments. The most conclusive result obtained during the semester is that the system has the ability to consistently produce < 1 NTU water at a V_{SedUp} of 2 mm/s and a $\Pi_{Capture}$ of 0.1. This performance is maintained even when the incoming raw water is as low as 3 NTU, as can be seen from Figure 9.

Although the team has not managed to optimize other parameters as planned, the potential to increase V_{SedUp} from the current value of 1 mm/s to 2mm/s represents exciting possibilities for AguaClara, due to three main reasons. Firstly, this means that an AguaClara plant can produce water on the order of 0.1 NTU with the addition of a stacked rapid sand filter (assuming the SRSF has a $pC*$ of 1). Secondly, this means that the plant flow rate in existing AguaClara plants can be doubled, and the plan view area of sedimentation tanks in future AguaClara plant designs can be halved. Last but not least, this result also means that good performance can be maintained even at a $V_{Capture}$ of 0.2 mm/s, as compared to the current design $V_{Capture}$ of 0.1 mm/s. This suggests that the important parameter to design for is not the absolute value of the capture velocity, but rather the ratio of capture velocity to upflow velocity. Finally, it is important to emphasize that the achievement of < 1 NTU effluent turbidity in the system was contingent on the maintenance of a floc blanket within the sedimentation tank.

Another significant result from this semester's experiments is that recycling flocs at a floc recycle ratio of 0.1 from the top of the floc blanket did not seem to interfere with floc blanket maintenance. Indeed, floc recycle seemed to improve flocculator performance by increasing the solids concentration within the flocculator when the plant influent was 3 NTU. Meanwhile, decreasing coagulant dosages seemed to reduce the benefit of floc recycle, by thinning out the floc blanket. If these observations persist even after repeated experiments, the team recommends prioritizing the maintenance of the floc blanket. Floc recycle can still be implemented to reduce the flocculator length, which will also result in significant cost savings.

6 Future Work

Once data is obtained about the optimization of the coagulant dose, the floc recycle ratio can be optimized. Previously it was observed that at a floc recycle ratio of 0.05, flocs began to settle out in the floc recycle line. This can be prevented by using a smaller inner diameter floc recycle line, which will increase velocity through the line for the same flow rate. Optimal floc recycle ratio may depend on V_{SedUp} due to the effect of upflow velocity on the floc blanket density, and it would be valuable to know the relationship between the two.

The location of the floc recycle influent line could be optimized. Currently the line pulls flocs out of the top of the sedimentation tank, and this increases the V_{SedUp} in the part of the sedimentation tank that is below the floc recycle influent line. This could be detrimental to the formation and maintenance of a floc blanket, but if floc recycle ratio is decreased, then this effect also decreases. It would be interesting to vary the location of the floc recycle influent line and observe the impact on plant performance.

Other future work includes optimizing the flocculator length and the capture velocity ratio, as per the Spring 2012 Challenges[1]. Since the system has multiple degrees of freedom, it is not possible to have every parameter exactly optimal. In order to make decisions about which parts of the plant to optimize, the team recommends prioritizing parameters based on cost. It will be helpful to develop some preliminary cost criteria that illustrates which parts of the plant are the most expensive based on both construction and maintenance costs. With these costs as a guideline, the next team can then identify the processes that will have the most significant impact if they are reduced. Once this is developed, decisions can be made as this project goes forward about which parameters to keep constant at optimal values.

References

[1] AguaClara/Flocculator and Sedimentation Optimization. Rep. Cornell University, 11 Jan. 2012. Web. 23 Feb. 2012. <https://confluence.cornell.edu/download/attachments/165972596/FSO.pdf?version=2&modific

[2] Freeman, Jill, Wang Mahina, Khan Saied, and Hurst Matthew. AguaClara - Sedimentation Tank Hydraulics. Rep. Cornell University, 15 Dec. 2011. Web. 23 Feb. 2012. <https://confluence.cornell.edu/download/attachments/117756976/Final+Report+Fa+2011.pdf

[3] Hurst, Matthew W. "Evaluations of Parameters Affecting Steady-State Floc Blanket Performance." Thesis. Cornell University, 2009. AguaClara-Floc Blanket MS Thesis. Cornell University. Web. 21 Feb. 2012. <https://confluence.cornell.edu/display/AGUACLARA/Floc+Blanket+MS+Thesis>.

[4] Hurst, Matt, Monroe Weber-Shirk, Tanya Cabrito, Cosme Somogyi, Michael Adelman, Zachary Romero, Richard Pampuro, Rachel Phillipson, Sarah Long, Colette Kopon, Ying Zhang, Ashleigh Sujin Choi, Adela Kuzmiakova, Jae Lim, Alexander Duncan, Christine Catudal, Elizabeth Tutunjian, Ling Cheung, Kelly Kress, Tiara Marshall, and Leonard W. Lion. AguaClara/The Effect of Floc Roll-up on Clay-Aluminum Hydroxide Flocs. Rep. Cornell University, 2011. Web. 23 Feb. 2012. <https://confluence.cornell.edu/download/attachments/147947701/PSS+Final+Report.pdf?vers

[5] McLane, John C. "Water Quality Improves by Recycling Settled Sludge." OPF, Vol. 30 Iss. 1, January 2004, Page Range 15-18

[6] Smith, Daniel. "Informe De Pruebas PAC En Plantas AguaClara." Message to Karen Swetland. 25 Jan. 2011. E-mail.

[7] Tse, Ian C., Karen Swetland, Monroe L. Weber-Shirk, and Leonard W. Lion. "Fluid Shear Influences on the Performance of Hydraulic Flocculation Systems." Water Research 45.17 (2011): 5412-418. Science Direct. Elsevier, 23 Aug. 2011. Web. 23 Feb. 2012. <http://www.sciencedirect.com/science/article/pii/S0043135411004544>.

[8] Weber-Shirk, Monroe L., and Leonard W. Lion. "Flocculation Model and Collision Potential for Reactors with Flows Characterized by High Peclet Numbers." Water Research 44.18 (2010): 5180-187. Science Direct. Web. 23 Feb. 2012. <http://www.sciencedirect.com/science/article/pii/S0043135410004136>.