# High Rate Sedimentation, Fall 2016

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**Abstract**

The Fall 2016 High Rate Sedimentation team investigated the effect of high upflow rates on maintaining a dense floc blanket and functional plate settlers. The team built a small-scale flocculator and tube model of the sedimentation tank in order to simplify the many experiment variation configurations.To analyze variables that effect effluent turbidity at an upflow velocity of 3 mm/s, which is roughly triple the standard AguaClara rate. Experiment 1 varied length of the tube settlers, Experiment 2 varied length of the floc blanket, and Experiment 3 attempted to increase the density of the floc blanket by adding mass. Experiments have verified that longer tube settlers and longer floc blankets improve sedimentation tank performance.

## Introduction

In water treatment plants, sedimentation was an important process which allowed particles to settle out and be removed from water. Part of the efficiency of the current AguaClara sedimentation design was derived from what was known as a floc or sludge blanket - a fluidized bed of suspended flocs, colliding in the bottom of the tank, as seen in Figure 1. These collisions allowed for many of the lightest and smallest particles, which would otherwise be carried out in the tank effluent, to be assimilated into larger flocs which settle out during their residence in the basin (Anyene et al., 2016). AguaClara also used plate settlers to catch the smallest particles that were not caught by the floc blanket. These inclined plates suspended in the sedimentation tank increased the available horizontal area for flocs to settle out.

Additionally, most AguaClara plants utilized vertical sedimentation tanks, which allowed the water to flow from top to bottom of the tank, through the floc blanket. This could seen in Figure 1, as the water flows from the bottom righthand corner, through the floc blanket, and out the top of he tank. Because the water flowed from the bottom to the top of the tank, the the flow velocity which maintained the floc blanket was known as upflow velocity. Although the time that the water spent in an AguaClara sedimentation tank, or residence time, was short compared to industry standards, sedimentation usually took around three times longer than the next slowest process of flocculation. This lengthy residence time translated into an allocation of plant area that, while smaller than the industry standard, was nonetheless the largest component of the treatment process.

Figure 1: The floc blanket reached the top of the floc weir and then wasted into the floc hopper, as seen on the lefthand side of the apparatus. The jet reverser can be seen in the bottom righthand corner of the apparatus (Anyene et al., 2016)

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The Fall 2016 team built upon the work of the Spring 2016 team, and performed three types of experiments to understand sedimentation tank performance under upflow velocity of 3 mm/s. This was because 3 mm/L was the highest rate which could be achieved without the tube settler hitting the ceiling. The first type of experiment measured effluent turbidity against increasing floc blanket depth, the second type measured effluent turbidity against increasing tube settler length (and therefore varying capture velocity), and the third type increased the density of the floc blanket. If time allowed, the team would apply the most optimal configuration to the small-scale sedimentation tank built by the Spring 2016 team.

# Literature Review

Swetland (2014) illustrated in a model study that one main purpose of flocculation research was to increase the performance of the flocculator as well as the following steps (e.g. sedimentation and filtration) while minimizing overall construction and operation costs. As flocs formed, they would sediment due to their higher density compared to water's. The flocs must settle faster than the upflow velocity. As the flocs concentrated and fell down to the bottom of the tank, a floc blanket formed.

Hurst (2010) stated that presence of the floc blanket would enhance the removal of turbidity. With hydraulic residence time of the particles in the floc blanket decreasing, fewer collisions would take place and the overall performance would decrease. However, the upflow velocity of 3mm/s was not tested by Hurst2010. The 2016 Fall team would run experiments at 3mm/s upflow velocity and analyze the performances of sedimentation tank based on different designs.

Balwan (2016), a researcher from the International Journal of Innovative Research in Advanced Engineering (IJIRAE), explored the effect of the length of tube settler on effluent turbidity. As indicated in his report, increasing the length of tube settlers increased the percentage of turbidity removed (defined as percentage change between influence and effluent turbidity). With tube settlers in 45 degrees inclination angle and 60 cm length, turbidity removal was measured to be 80 percent (surface overflow rate 35000L/m$^2$/hr). However, his experiments only had three length variables (40cm,50cm,60cm) and longer tube settlers caused higher head loss. Due to the ceiling height, the tubes are supposed to shorter than a certain length, which would be studied by the team this semester.

Culp et al. (1968) used tubes to figure out the optimal slope of the tube settlers. Under laboratory conditions, a 60 deg angle provided continuous sludge removal while showing effective sedimentation performance. Future experiments could be based on Culp's2016 optimal result, and other aspects, such as length, could be changed.

## Previous Work

In Spring 2016, High Rate Sedimentation was split into two subteams, one focusing on the floc blanket, and another focusing on the plate settlers. The floc blanket subteam built a small scale model of half of the sedimentation tank to maintain the floc blanket stable at upflow velocity from 1-4mm/s. By using this tank, the team ran experiments at different upflow velocities (1mm/s, 2mm/s, and 3mm/s) and plate settler positions. Floc blanket concentration and effluent turbidity were measured for every controlled experiment. It was confirmed that a very dense floc blanket was associated with low effluent turbidity.

The High Rate Sedimentation-Plate Settler team designed a coiled flocculator and two types of plate settlers, continuous and porous (Figure 2), to test the effluent turbidity. It was concluded that the addition of plate settlers concentrated the floc blanket at high upflow velocity but no other solid conclusions could be drawn from the plate settlers geometry. This semester, the High Rate Sedimentation team looked at each variable separately by changing the height of the floc blanket and length of the tube settlers separately, using only continuous plate settlers.

Figure 2: The Spring 2016 team found no conclusive evidence that one type of plate produces lower effluent turbidity than the other.(Cheng et al., 2016)

Inspired by the Fall 2015 team, the Fall 2016 team improved upon the Fall 2015 model design by adding interchangeable parts, allowing variables to be evaluated individually. However, many aspects of the Fall 2015 model were incorporated into the Fall 2016 design. During a sand column experiment, the Fall 2015 team observed that a fluidized sand bed was very dependent on the 60 degree slant angle, which the Fall 2016 used to determine the bend angle of the tube settlers. In addition, the Fall 2015 team chose clear PVC pipes to represent their sedimentation tank, which saved space and construction time. Hence, the Fall 2016 team also used PVC tubes to build a sedimentation tank model, and designed experiments based on the PVC pipes. The Fall 2015 team put the floc weir above the bent connection between the tube settler and recirculator, the portion of the sedimentation tank model that represents the floc blanket. The Fall 2016 team improved this design by placing the floc weir below the bent connection. Now the height of the floc blanket can be controlled by the position of the floc weir in relation to the water entrance point.

# Methods

## Flocculator

### APPARATUS

Although the Spring 2016 HRS team built a flocculator, it was designed for a slower upflow velocity, and was too large for this semester's small-scale tube model. So, the Fall 2016 team decided to design another a flocculator more suited to the new needs. The flocculator must accommodate the same flow as the model sedimentation tank. Additionally, AguaClara traditionally designs flocculators for a G$\theta$ of 40,000, where a higher G$\theta$ indicates better flocculated water coming into the sedimentation tank. Our team decided to use a target G$\theta$ of 20,000 in order to ensure that our sedimentation tank would function under sub-optimal conditions.

The tube model had an upflow velocity of 3 mm/s and a nominal diameter of 0.824", for a flow of 1.032 mL/s. Given this upflow velocity and the aforementioned G$\theta$ value, the equations listed below were used to choose a flocculator diameter of 1/8" and corresponding length of 9.2m. The tubing sold that most closely matched our requirements was 100 ft Masterkleer PVC clear tubing with a diameter of 1/8".

$$\mathrm{L}_{\mathrm{Floc}} = \theta_{g}oal * \frac{4 * Q_{R}eactor}{\phi * D_{F}loc^{2}} \tag{1}$$

The pipe used to coil the flocculator tube cannot be too small, which would cause flocs to get stuck in the bends, and it can't be too big, which would result in a lot of unnecessary space usage. Therefore, a cardboard tube with a diameter of 3" and a length of 32" was used to coil the flocculator tubing as shown in figure5. To save space on the workbench, the entire flocculator apparatus was hung from the workbench.

A 1/8" push-to-connect was used to connect the flocculator tubing to the influent water, and a male adapter was used to connect the flocculator tubing to the 3/4" recirculator pipe.

## Inputs

$Q_{reactor} := 1\frac{mL}{s}$ The flow rate of the system

$G\theta_{goal} := 20000$ Target G*theta to design flocculator.
Traditionnally it was 40000.

$D_{Floctube} := \frac{1}{8}\cdot in$ Diameter of flocculator tubing

$R_c := 10\cdot cm$ Radius of curvature (the radius of the tube the flocculator is wrapped around

## Calculations

$Re_{pipetransition} := 2100$ $\nu := 1\cdot 10^{-6}\cdot\frac{m^2}{s}$ $\varepsilon_{PVC} := 0.12mm$ $Re_f(Q,D,\nu) := \frac{4\cdot Q}{\pi\cdot D\cdot\nu}$

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$f(Q,D,\nu,\varepsilon) :=$
    $f \leftarrow \frac{0.25}{\left(\log\left(\frac{\varepsilon}{3.7D} + \frac{5.74}{Re_f(Q,D,\nu)^{0.9}}\right)\right)^2}$ if $Re_f(Q,D,\nu) > Re_{pipetransition}$
    $f \leftarrow \frac{64}{Re_f(Q,D,\nu)}$ otherwise
    return f
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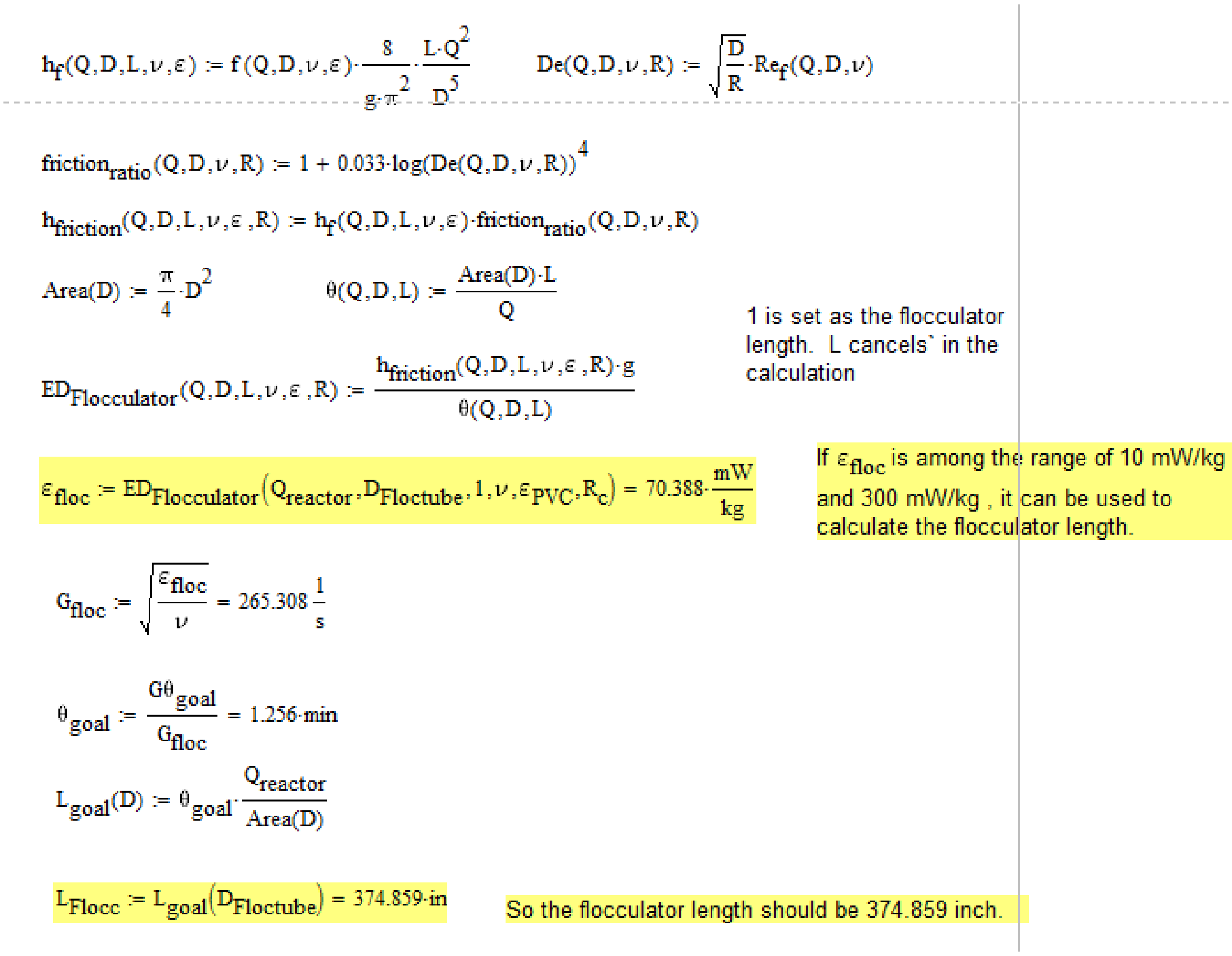

$h_f(Q,D,L,\nu,\varepsilon) := f(Q,D,\nu,\varepsilon)\cdot\frac{8}{g\cdot\pi^2}\cdot\frac{L\cdot Q^2}{D^5}$ $De(Q,D,\nu,R) := \sqrt{\frac{D}{R}}\cdot Re_f(Q,D,\nu)$

$friction_{ratio}(Q,D,\nu,R) := 1 + 0.033\cdot\log(De(Q,D,\nu,R))^4$

$h_{friction}(Q,D,L,\nu,\varepsilon,R) := h_f(Q,D,L,\nu,\varepsilon)\cdot friction_{ratio}(Q,D,\nu,R)$

$Area(D) := \frac{\pi}{4}\cdot D^2$ $\theta(Q,D,L) := \frac{Area(D)\cdot L}{Q}$

$ED_{Flocculator}(Q,D,L,\nu,\varepsilon,R) := \frac{h_{friction}(Q,D,L,\nu,\varepsilon,R)\cdot g}{\theta(Q,D,L)}$

1 is set as the flocculator length. L cancels` in the calculation

$\varepsilon_{floc} := ED_{Flocculator}\left(Q_{reactor},D_{Floctube},1,\nu,\varepsilon_{PVC},R_c\right) = 70.388\cdot\frac{mW}{kg}$

If $\varepsilon_{floc}$ is among the range of 10 mW/kg and 300 mW/kg , it can be used to calculate the flocculator length.

$G_{floc} := \sqrt{\frac{\varepsilon_{floc}}{\nu}} = 265.308\,\frac{1}{s}$

$\theta_{goal} := \frac{G\theta_{goal}}{G_{floc}} = 1.256\cdot min$

$L_{goal}(D) := \theta_{goal}\cdot\frac{Q_{reactor}}{Area(D)}$

$L_{Flocc} := L_{goal}\left(D_{Floctube}\right) = 374.859\cdot in$

So the flocculator length should be 374.859 inch.

Figure 3: The equations used to decide the flocculator tube diameter and length.

Figure 4: A short piece of pipe ensures the small clay tube will remain submerged.

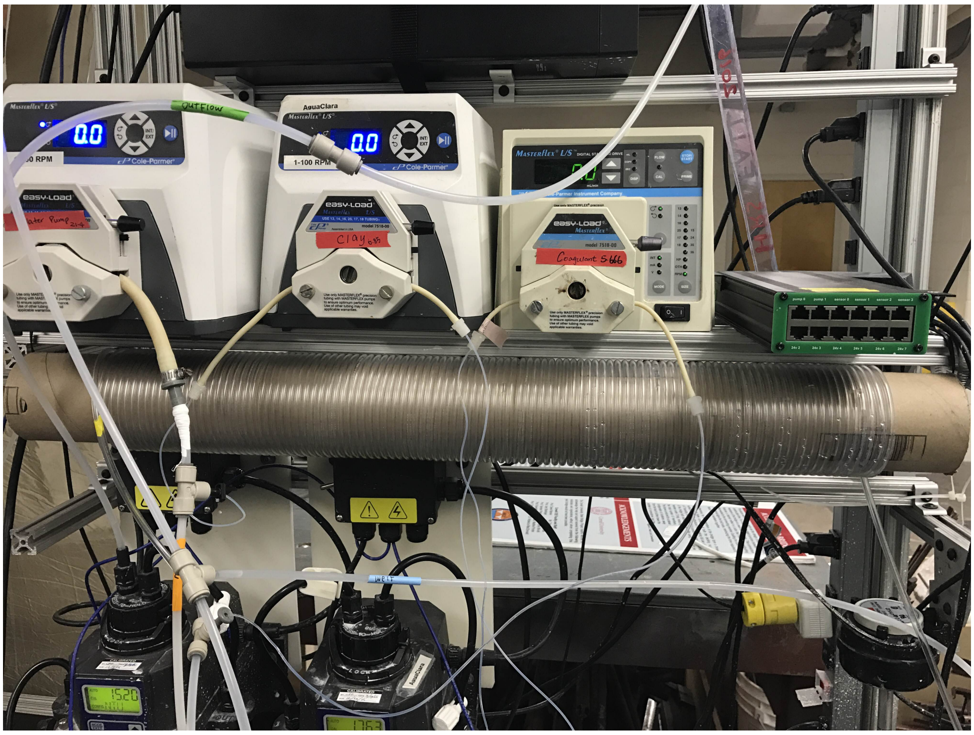

Figure 5: To save space, the flocculator was suspended above the table using zipties.

## Floc Blanket Height Experiments

### APPARATUS

The height of the floc weir at the top of the floc recirculator, also viewed as the length of the recirculator, controls the height of the floc blanket. In a typical AguaClara plant, the floc blanket height is around 1.5m. Given the limited lab space and ceiling height, the Fall 2016 team decided that the maximum experimental recirculator length should be 1.5m. As the team wanted to test three recirculator lengths, 1.0m and 0.5m were chosen not according to any equation, but for simplicity of measurement and design.

To experiment with a 0.5m recirculator, a 0.45m pipe is simply attached to the floc weir portion with a modified compression fitting and to the flocculator using a glued-on transition piece,as shown in figure 6. To experiment with the 1.0m recirculator, a similar procedure is followed with a 0.95m pipe. However, to experiment with the 1.5m recirculator, the 0.5m pipe is attached to the 0.95m pipe using a modified compression fitting, as seen in Figure 7. The middle portion of the compression fitting was cut out, and the two end pieces were reglued together, allowing more of the clear tube to be visible.

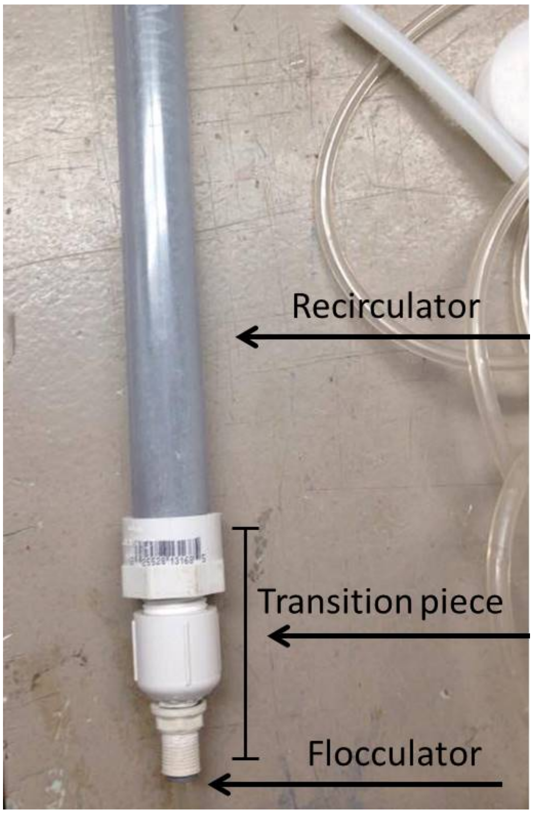

Figure 6: The transition piece connects the recirculator to the flocculator.

Figure 7: The compression fitting provides a removable, waterproof connection between the recirculator and the floc weir, allowing different recirculator pieces to easily be swapped in and out.

The first two pipes are 5cm shorter than the intended recirculator length to account for extra length in the floc weir piece and in the compression fittings. As explained later in the report, a pipe of nominal diameter 0.824" was required for the tube settlers, and therefore also had to used for the floc weir and recirculator sections of the model.

The floc weir was constructed using 15 cm 3/4" and 1/2" clear PVC pipe, chosen due to availability. A hole was drilled 5cm above the bottom of 3/4" pipe and the 1/2" pipe was bent and welded to the 3/4" pipe at the hole. There was no specific angle chosen for bending the 1/2" pipe.

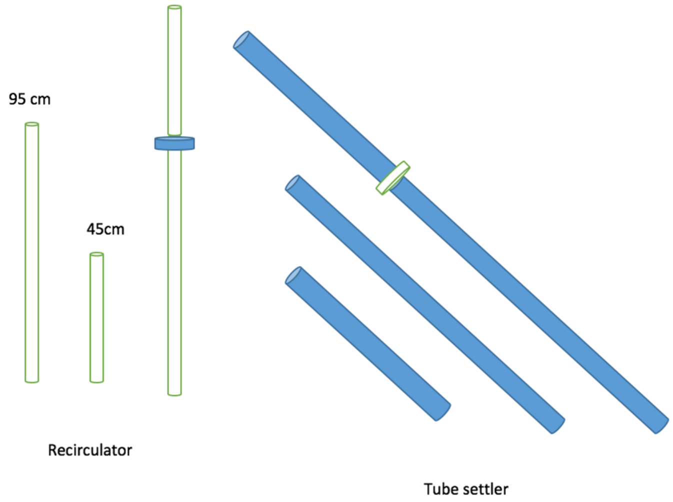

Figure 8: The length scale of recirculator and tube settler.

## PROECEDURE

The 0.5m length recirculator was cut and connected with flocculator to measure the effluent turbidity in three hours. The influent water pump was set to 16.5RPM to maintain 3mm/s upflow velocity. The clay concentration was 2g/L and the clay pump was set to 15.8RPM to maintain the 100 NTU turbidity for influent. The coagulant concentration was 55.156mg/L. The coagulant pump was set at a high speed of 56.8RPM to speed up the time to floc blanket formation.

Before each experiment, the flocculator was cleaned out and the entire system was checked for leaks.

After the measurement with 0.5m recirculator, the 1m recirculator was used to measure effluent turbidity and other conditions were maintained. Then the 0.5m and 1m recirculator were combined using a coupling to create a 1.5m recirculator, with which the effluent turbidity was measured at the same initial conditions as before. The 53in tube settler was used for all three experiments.

## Tube Settler Length Experiments

### APPARATUS

The settle capture velocity of a sedimentation tank is a property of tank geometry, and is defined as the downward velocity of the slowest settling particle that the sedimentation tank can reliably capture. [from CEE 4540 Sedimentation PPT Fall 2016]. That is, if a particle is falling at or faster than the capture velocity, the sedimentation tank will retain the particle. Any particle falling slower than the capture velocity will exit the tank in the effluent.

Capture velocity is given by Equation 2, where D is the spacing between the plate settler or diameter of the tube settler, L is the length of the settler, $V_{upflow}$ is the upflow velocity, and $\theta$ is angle of the settler compared to the horizontal.

$$\mathrm{V_{cap}} = V_{uplow} \cdot \frac{\frac{D}{sin\theta}}{L \cdot \sin\frac{\pi}{3} \cdot cos\frac{\pi}{3} + \frac{D}{\sin\theta}} \tag{2}$$

AguaClara plants traditionally use a capture velocity of 0.12 mm/s. Given an upflow velocity of 3 mm/s and an angle of 60 degrees, the Fall 2016 team had to choose a length and related diameter of the tube settler. A tube with an inner diameter of 0.5" was difficult to work with and modify, while a diameter of 1" required a pipe length of nearly 7 feet. Thus, the Fall 2016 team chose to use a pipe of diameter 0.75", for a length of 53", or 4.4'.

In addition to testing sedimentation tank performance at a higher upflow velocity of 3 mm/s, the Fall 2016 team also decided to test varying the capture velocity at this higher upflow velocity. Since upflow velocity and inner diameter were fixed in the model, the capture velocity could only be changed by changing tube length.

Since 2016 Fall team tested an upflow velocity of 3 mm/s, and was restricted to the previously chosen tube diameter of 0.75", a higher capture velocity could be tested by decreasing tube settler length, while a lower capture velocity could be tested by increase tube settler length, according to Equation 2. Since the design was restricted by the height of ceiling, the Fall 2016 team decided to use tube settlers of lengths 30", 53", and 83" in the experiments.

### PROCEDURE

The effluent turbidity was measured when 53in, 30in, and 83in tube settlers were connected with the recirculator. The same 0.5 recirculator was used for all three experiments and the influent turbidity was maintained at approximately 100NTU. The recirculator experiment pump speeds were kept, with the water pump at 16.5 rpm, the clay pump at 12.7 rpm, and the coagulant pump 32 rpm. The clay concentration was 2g/L and the coagulant concentration was 55.156mg/L. Effluent turbidity data was collected using ProCoDA.

### ProCoDA Methods

ProCoDA was used to track both the influent and effluent for the duration of each experiment. The ON was set to 1 and the OFF was set to 0. The Influent Turbidity and Effluent Turbidity were added as set points.

# Results and Analysis

## Results

### Floc Blanket Height Experiment

For the effluent turbidity measurement at different recirculator lengths, the team expected the effluent turbidity to decrease as the recirculator became longer, meaning that the floc blanket would became longer. As the floc blanket increased in height, particles would have more chances to collide in the floc blanket and the effluent turbidity would decrease. However, as more flocs entered the system, the shear between particles also increased, which could lead to flocs breakup. For the floc blanket experiments, the team used an 73-inch tube settler for all three experiments, while varying the length of the recirculator. Influent turbidity was set at around 100 NTU and the effluent data was recorded after the system had reached steady state.

The experimental data verified the team's expectation. The effluent turbidity values were collected when effluent turbidity became relatively stable for each experiment. Figure 1 shows the effluent turbidity for recirculator lengths of 0.5m, 1m and 1.5m and the tube settler was 53in. As the 0.5m recirculator trial provided the highest effluent turbidity and 1.5m recirculator provided significantly lower effluent turbidity, it can be concluded that a longer recirculator (ie a longer floc blanket) produces lower effluent turbidity. The relationship between recirculator length and the effluent turbidity was plotted in Figure 1. As the recirculator length increased, the effluent turbidity decreased.

Figure 9: The floc blanket formed.

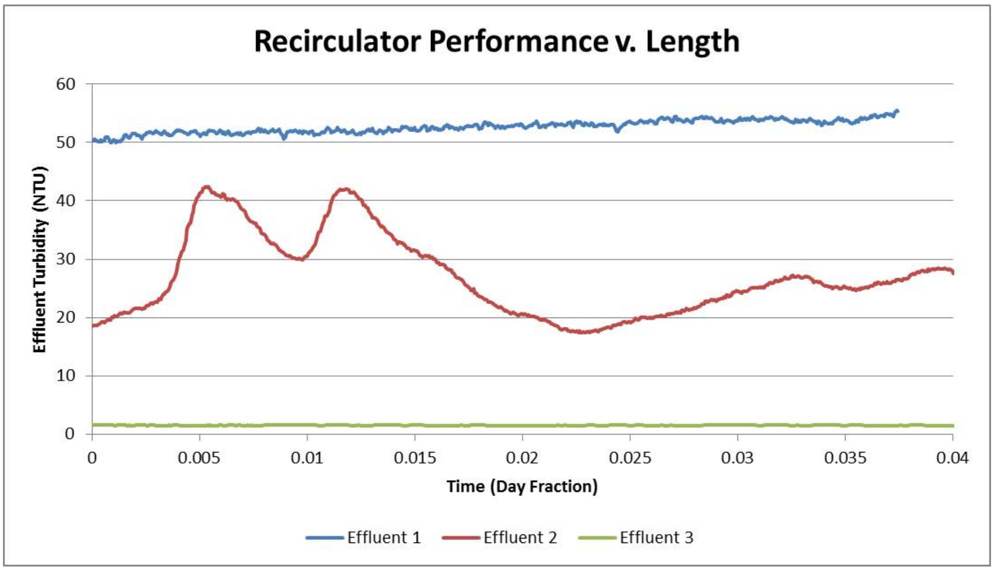

Figure 10: The effluent turbidities for the 0.5m, 1.0m, and 1.5m recirculators.

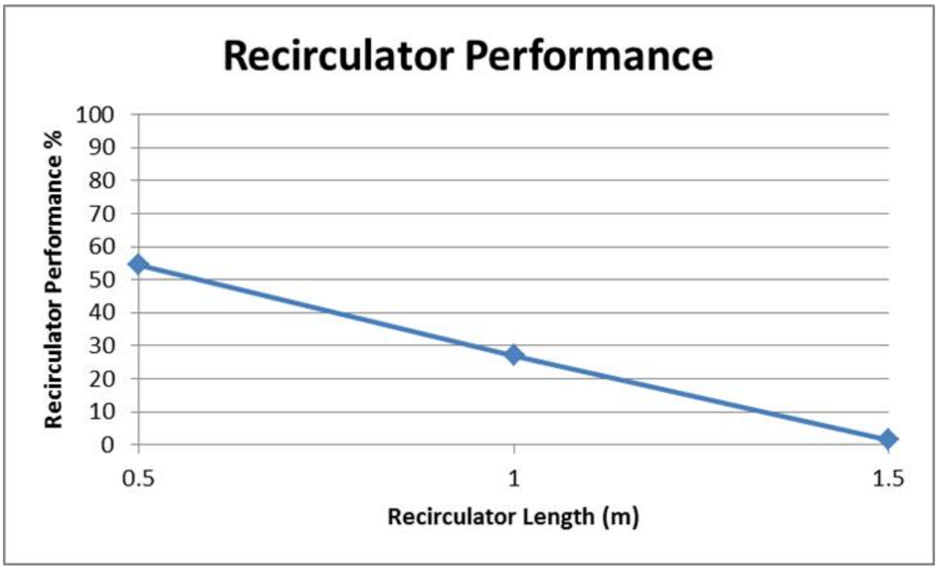

Figure 11: Recirculator performance as a function of length.

### Tube Settler Length Experiment

2016 Fall team ran experiments under 3 different tube settler length: 34 inch, 53 inch, and 73 inch. There was no previous work regarding how the tube settler length would influence the effluent turbidity, but the team expected that as the tube settler became longer, effluent turbidity would decrease as more flocs were captured by the tube settler.

The experimental result confirmed the expectation. As Figure 1 demonstrates, the effluent turbidity was highest when the tube settler was 34in and lowest when the tube settler was 73in. Figure 1 shows the relationship between tube settler length and effluent turbidity. As the tube settler became longer, the effluent turbidity decreased significantly.

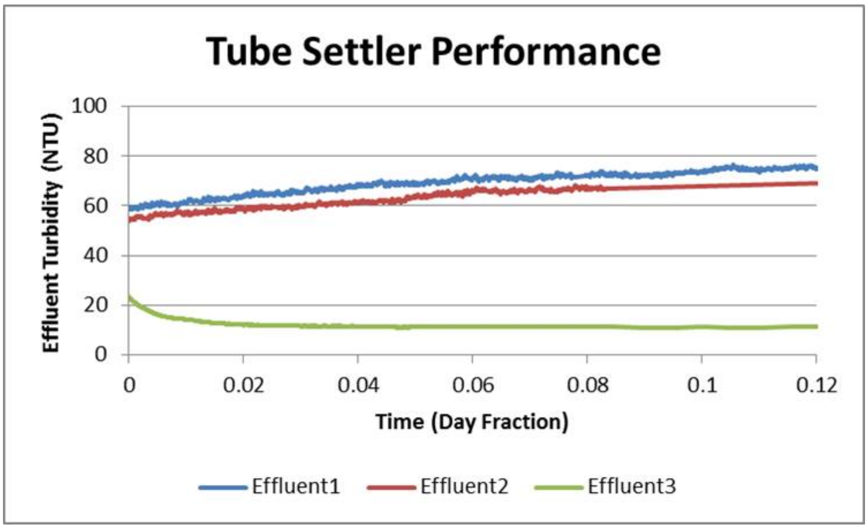

Figure 12: The effluent turbidities for the 34in, 54in, and 87in tube settlers.

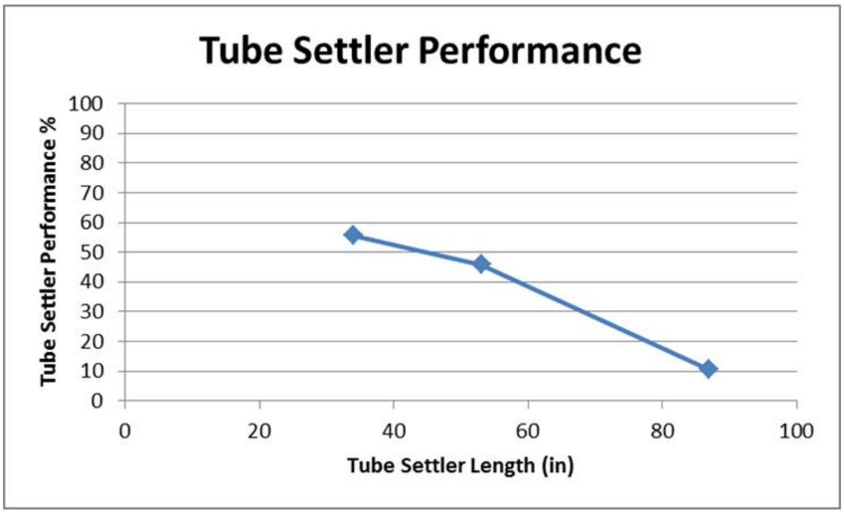

Figure 13: Tube settler performance as a function of length.

## Analysis

The main challenge encountered by the team during the design/ construction phase was how to connect the recirculator with the flocculator. While the team initially planned to use compression fittings on all connections, the correct size of compression fitting was difficult to find online. Thus, the team decided to use male adapters to connect the model to the flocculator and effluent pipe. The adapters were simply glued to bottom pipes. In addition, due to the length of a compression coupling, one section of the otherwise transparent model was covered by the coupling, and therefore cannot be observed. In order to increase visibility, the team cut two ends of the coupling and re-glued these two ends together.

While the team expected for design and construction to last only about a month, the team spent much longer constructing the model, mainly due to the fact that the chosen pipe was thinner than the Spring 2016 sedimentation tank model, and parts were difficult to encounter. The leaking and air bubble issue also cost the team about another month.

The floc blanket experiments performed as expected, with effluent turbidity decreasing as recirculator length increased. These experiments went according to plan.

The tube settler experiments had a few more challenges. Although several experiments were run for the longest (73in) tube settler, the floc blanket took a long time to form, and the effluent turbidity values were not stable. However, the team resolved this issue near the end of experimentation, and the team was able to collect some good data points.

The team expected as tube settler length increased, the effluent turbidity would decrease, as experimental data confirmed. As tube settler length increased, the capture velocity decreased and the settler was able to catch smaller flocs. These flocs accumulated in the tube settler and slid back into the floc blanket or out of the effluent weir, thereby decreased effluent turbidity.

# Conclusions

As the previous year team had confirmed that the floc blanket with higher concentration was associated with lower effluent turbidity, the Fall 2106 team investigated how floc blanket height and tube settler length influenced effluent turbidity. The team found that with longer floc blanket height, the effluent turbidity decreases. This finding could contribute to updated AguaClara designs for sedimentation tanks and floc blankets; more height would aid the performance of a high rate sedimentation tank.

The other discovery of the team was that longer tube settler also enable the sedimentation tank to perform better. As the tube settler increased from 30 in to 73 in, the effluent turbidity had an apparent drop and a denser floc blanket formed. This discovery was exciting because few relevant experiments about tube settler length were found before the tube length experiment was run. As the optimal bent angle of tube settler had been found to be 60 degrees, extending the length of the tube settler would further improve the performance of the high rate sedimentation tank.

## Future Work

Through various experiments, the 2016 Fall High Rate Sedimentation team explored the relationships between floc blanket height and effluent blanket and relationship between tube settler length and effluent turbidity. An optimal pair of recirculator and tube settler could be decided from these findings. However, the team did not have time to apply these findings into a small-scale sedimentation tank. Therefore, future work could focus on applying the experiment conclusions into the small-scale sedimentation tank.

2016 Fall High Rate Sedimentation team planed to change the angle of recirculator to see if better floc blanket would form without vertical recirculator. The team also hoped to change the density of floc blanket by adding sludge into the recirculator so that shorter time could be taken for the experiments. The team wondered if any particle other than clay that performed better in collision with clay particles.

Besides, 2016 Fall team ran the system under 3mm/s influent velocity. Even though the effluent turbidity was not low enough to meet the drinking water quality, a higher influent velocity was still needed to be tested for the goal of decreasing plant area.

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# Semester Schedule

## Task Map

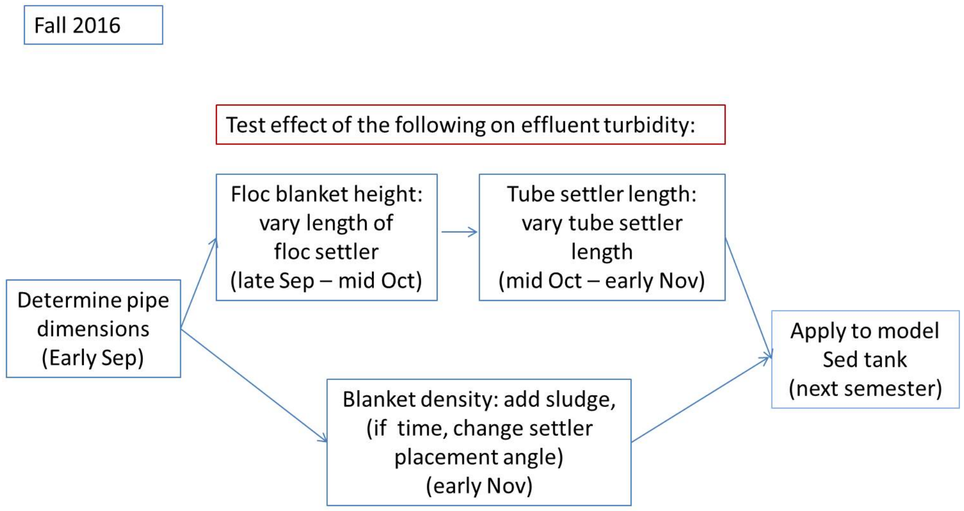

Figure 14: The task map illustrated above is the comprised of the work the Fall 2016 subteam planned to complete over the course of the semester.

## Task List

Week 4 (09/12-09/16)

- Determine the dimensions of pipes using MathCad
- Decide the amount of pipes and purchase if needed
- Draw out the rough models of experimental pipes -completed

Week 5 (09/19-09/23)

- Wield pipes based on previous week's design
- Determine variables for testing influence of floc blanket height for effluent turbidity -completed

Week 6 (09/26-09/30)

- Run the first group of experiments by changing perpendicular part of bent pipes
- Record and analyze data collected -completed

Week 7 (10/03-10/07)

- Continue to run more trials if needed for the first group of experiments
- Determine variables for testing influence of tube settlers' length for effluent turbidity-completed

Week 8 (10/12-10/14) (Fall break)

- Run the second group of experiments by changing bent part of bent pipes
- Prepare for the Symposium -completed

Week 9 (10/24-10/28)

- Summarize the feedbacks from Symposium
- Continue to run second group of experiments -completed

Week 10 (10/31-11/04)
- Analyze data collected from second groups of experiments
- Make necessary adjustment and continue experiments-completed

Week 11 (11/07-11/11)
- Compare data collected from two groups of experiments
- Make hypothesis regarding the relationships behind the data-completed

Week 12 (11/14-11/18)
- Design new experiments based on hypothesis–completed

Week 13 (11/21-11/22)
- finished running all experiments needed –completed

Week 14 (11/28-12/02)
- Summarize the two groups of experiments
- Final Report -completed

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