High Rate Sedimentation—Plate Settlers
Spring 2016

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Abstract

This semester, the goal of the High Rate Sedimentation - Plate Settlers team was to maintain a suspended layer of colloidal particles (flocs) at upflow velocities higher than 1 mm/s. The suspended layer, referred to as the floc blanket, circulates flocs, enhances flocculation and is self-cleaning. As the floc blanket grows in height, it spills over a weir into a sludge collection chamber to prevent sludge build-up inside the sedimentation tank. Increasing the upflow velocity in the sedimentation tank decreases the necessary plan-view area and cost of construction. A high density floc blanket is necessary to prevent flocs from escaping the sedimentation tank at higher velocities. The High Rate Sedimentation - Plate Settlers team explored different plate settler geometries in the sedimentation tank to concentrate the floc blanket.

Introduction

Sedimentation is the slowest process and requires the largest plan-view area in AguaClara water treatment plants. Larger AguaClara plants require more construction materials and labor, which directly translates into higher construction costs. The high cost for a large treatment plant is often a setback for low income communities that have limited budget. The High Rate Sedimentation - Plate Settlers team looked into decreasing the size of AguaClara treatment plants to make the plants more affordable. A sedimentation tank with smaller plan-view area requires a higher upflow velocity inside the tank to maintain the same flow rate. However, a higher upflow velocity pushes lighter flocs out of the tank and makes it difficult to maintain the floc blanket.

In order to reduce the number of flocs escaping the sedimentation tank, the High Rate Sedimentation - Floc Blanket and High Rate Sedimentation - Plate Settlers teams focused on producing a more concentrated blanket. The concentrated floc blanket increases the number of collisions between flocs because the flocs are closer together. As flocs collide, they combine to form larger particles that settle faster in water.

To maintain a floc blanket after increasing the upflow velocity, the falling terminal velocity needs to be increased. The High Rate Sedimentation - Plate Settlers team tested various plate settler geometries in a lab-scale sedimentation tank. Plate settlers are designed to increase floc blanket density by capturing and recycling flocs back into the floc blanket.

Literature Review

Sedimentation Theory

Coagulant is added into the water and acts as an adhesive that attaches particles to each other when they collide during flocculation. Common coagulants include polyaluminum chloride (PACl) and aluminum chlorohydrate (ACH). Flocculation is the process in which nanoparticles aggregate into larger and denser particles, also known as flocs (Weber-Shirk, 2015). Newly-formed flocs then proceed to undergo sedimentation because they have a higher density than water. For the floc particles to stay in the sedimentation tank, they must settle faster than the upflow velocity in the tank (Weber-Shirk, 2015).

Current AguaClara sedimentation tanks, as shown in Figure 1 have a sloped bottom design with downward-facing, high velocity jet reversers. The sloped bottom design allows settling floc to slide down toward a central point at the bottom, and then the jet keeps those flocs in suspension as shown in Figure 2. This design prevents accumulation of sludge at the bottom of the sedimentation tank.

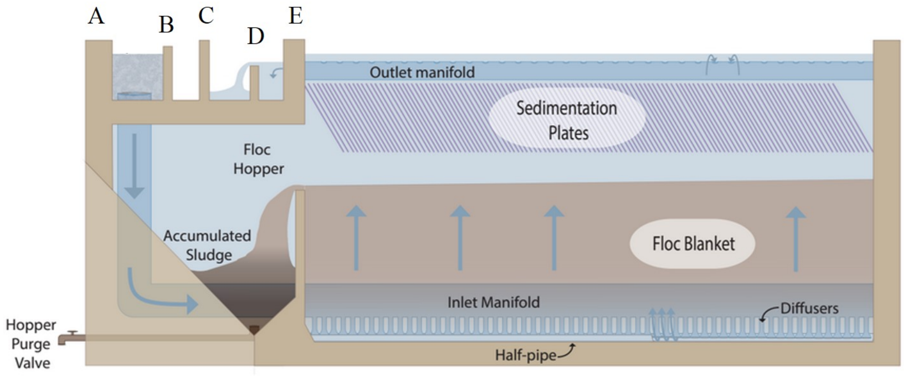


Figure 1: A side-view diagram of the current AguaClara sedimentation tank shows the process flocs go through during sedimentation. Water from the flocculator enters the sedimentation tank through diffusers on the inlet manifold. As the floc blanket grows in height, excess flocs spill over into the floc hopper and accumulate as sludge. Any small particles that escape the floc blanket can be captured in the sedimentation plates.

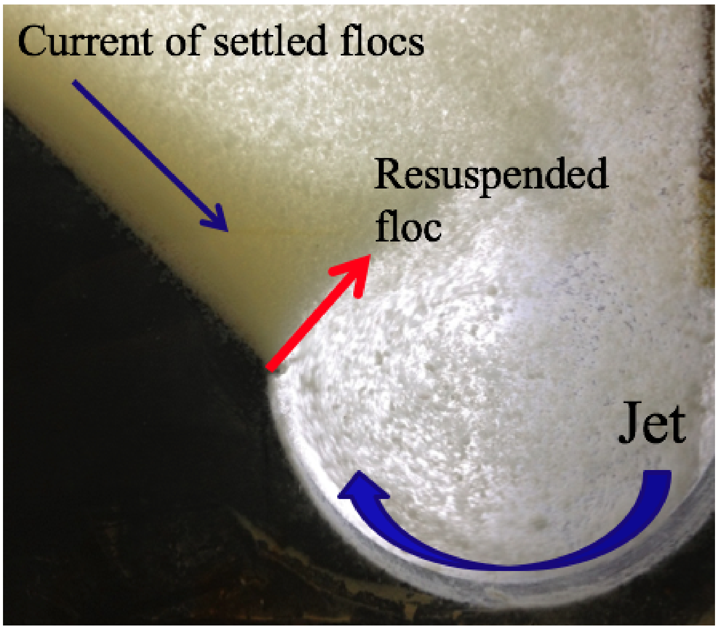


Figure 2: The jet reverser shown above lies at the bottom of the sedimentation tank. A current of settled flocs slides down the sloped bottom of the sedimentation tank. The jet enters the sedimentation tank in the downward direction, and is reversed by the rounded jet reverser at the bottom of the tank. When the current of settled flocs meets the jet, the flocs are resuspended(Weber-Shirk, 2015).

Floc Blankets

Current AguaClara sedimentation tanks are built with high velocity jet diffusers that are coupled with a jet reverser in order to suspend flocs and create a floc blanket. While these particles are moving in the blanket, they collide with each other and become larger particles. Instead of leaving out the top of the sedimentation tank, the larger flocs stay suspended in the floc blanket at the bottom of the tank, providing additional flocculation for water flowing through the sedimentation tank. This results in a lower effluent turbidity leaving the sedimentation tank. Previous floc blanket research concluded that the system was most effective at an upflow velocity of approximately 0.8 mm/s (Hurst et al., 2014). Slower upflow velocities cause particles to settle and create disturbance to the influent jets (Hurst et al., 2014). Hurst concluded that a decreased hydraulic residence time in the floc blanket results in fewer collisions in the floc blanket and a reduction of overall performance. (Hurst et al., 2014).

Plate Settlers in High Rate Sedimentation

Traditional high rate sedimentation relies on the use of sloped insertions and gravitational settling properties to obtain settling efficiencies comparable to those of conventional rectangular settling tanks (Yao, 1970). The size of flocs that can be captured by the sedimentation tank is described by its capture velocity. Capture velocity can be determined by dividing the total flow over total projected horizontal area in the sedimentation tank. The sloped insertions provide more horizontal area for flocs to settle, allowing the tank to catch smaller particles. Since there are multiple forces acting on each floc, it is expected that the particle has a trajectory vector that is the sum of the sloped upflow velocity and the increasing downward vector of gravity. In this design, there is a shorter distance for particles to fall due to sloped plate insertions, and the sedimentation tank can catch smaller particles that fall more slowly.

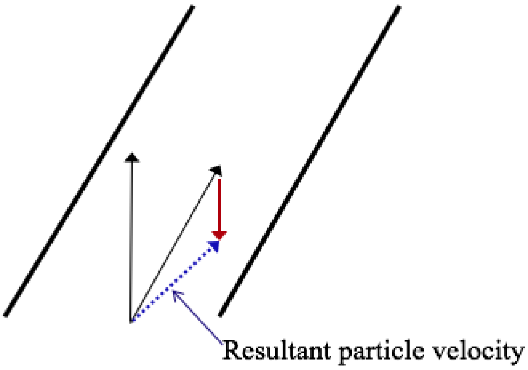


Figure 3: Plate settlers allow smaller flocs to be captured by providing more horizontal surface area. The vertical arrow pointing up is the upflow velocity. The sloped black arrow is the velocity vector of the floc particle without the effects of gravity. The red arrow is the velocity vector due to gravity. The blue arrow is the resultant particle velocity vector (Weber-Shirk, 2015).

Plate Settlers Slope

It is important accumulated flocs on plate settlers can slide down back into the floc blanket because this allows the plates to be self-cleaning. Flocs slid down most effectively when the tube settlers were angled between 45°and 60°(Culp et al., 1968) based on the density of flocs. For high floc volumes, a 60°angle allowed flocs to continuously slide down the plates while keeping the sedimentation tank functional and efficient (Culp et al., 1968). Flocs that slide down also add to the floc blanket and increase its concentration, which increases floc aggregation.

Previous Work

In the fall of 2015, the High Rate Sedimentation team conducted two experiments to investigate the behavior of fluidized sand to simulate the behavior of flocs at various upflow velocities and tube settler angles. Sand was used in the first experiment instead of flocs because fluidized sand can also model behavior similar to that of fluidized floc particles. Afterwards, the High Rate Sedimentation team tested the flow patterns of flocs at different combinations of flow rate and coagulant dose (Anyene et al., 2015).

In the first experiment, the Fall 2015 High Rate Sedimentation team set up a tube apparatus containing sand, which was then tilted at different angles and operated at different upflow velocities. The results of this experiment showed that the fluidized sand height in the tube decreased as the column was slanted, and increased as the upflow velocity was increased(Anyene et al., 2015). It was concluded that fluidized particles settled and slid down most efficiently when the apparatus was at a 60°angle. These findings were similar to previous research which found that flocs slid down most effectively when tube settlers were angled between 45°and 60°(Culp et al., 1968).

In the second experiment, a single plate settler and twenty small tube settlers were inserted in series into the same sedimentation column. The single plate settler, with a capture velocity of 1 mm/s, was placed at the bottom of the sedimentation column to capture and recycle the big flocs. Twenty small tube settlers, with capture velocities of 0.12 mm/s, were placed above the plate settlers to capture smaller flocs. A floc hopper was attached to the plate settlers at a 90°angle.

The Fall 2015 High Rate Sedimentation team tested the performance of the series of settlers with an upflow velocity that was increased by a factor of five. It was concluded that at a higher upflow velocity, the plate settler at the bottom still could recycle settled flocs and stabilize the floc blanket. However, the tube settlers at the top could not capture the small flocs because the space between the tube settlers was too narrow and caused floc roll up.

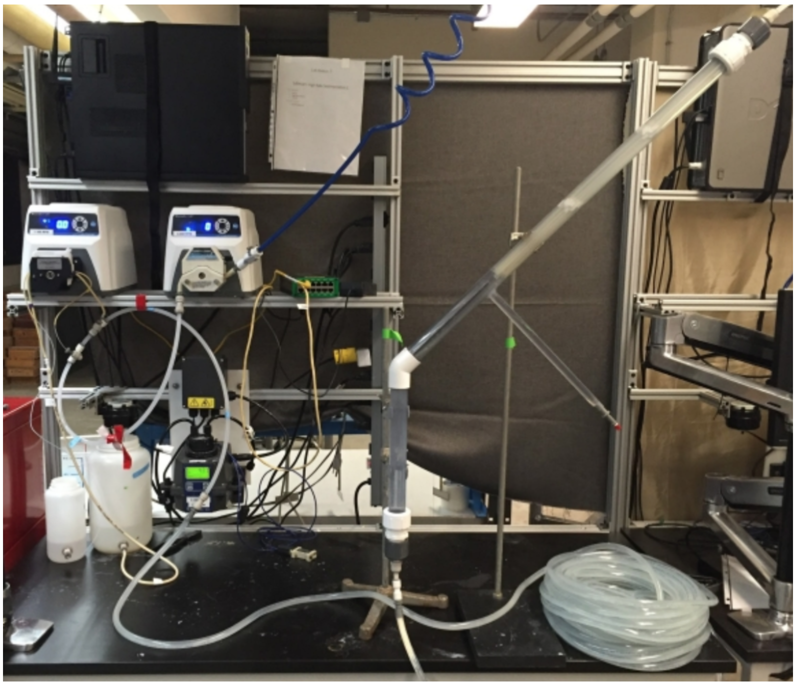


Figure 4: The Fall 2015 High Rate Sedimentation team used a 2.54 cm (1 inch) sedimentation tube to achieve a 5 mm/s upflow velocity. In front is a vertical sedimentation tube with a 45°angle tube settler that represents a small section of an actual sedimentation tank.(Anyene et al., 2015).

The Fall 2015 High Rate Sedimentation team concluded that the general physics of flocs could be used to design the next iteration of the high rate sedimentation tank. The team suggested building a larger apparatus to avoid issues with plate and tube settler spacing and floc roll-up (Anyene et al., 2015).

Methods and Discussion

Coiled Flocculator

Experimental Apparatus Design

The lab-scale sedimentation tank designed for this semester was much larger than the sedimentation column used in the semester of Fall 2015 in order to modify the inside of the sedimentation tank. A larger tank requires a higher flow rate to maintain the same upflow velocities tested in the Fall 2015 semester. The High Rate Sedimentation - Floc Blanket and High Rate Sedimentation - Plate Settlers teams conducted research using similar setups, so they each focused on a different part of the apparatus. The High Rate Sedimentation - Floc Blanket team was in charge of designing and building a lab-scale sedimentation tank and the High Rate Sedimentation - Plate Settlers team was responsible for designing and constructing a flocculator that could produce easily visible floc at high flow rates.

Flocculator Design

The current AguaClara sedimentation tanks have an upflow velocity of 1 mm/s. The Spring 2016 High Rate Sedimentation - Plate Settlers team increased the upflow velocity by a factor of five in the new sedimentation tank design. Since the High Rate Sedimentation - Floc Blanket team decided on a sedimentation tank that has a 5 cm by 20 cm cross-section, the necessary flow rate to achieve a 5 mm/s upflow velocity was 50 mL/s. A 0.95 cm (3/8 in) diameter flexible polyvinyl chloride (PVC) tube flocculator was provided by the Fall 2015 High Rate Sedimentation team. If this flocculator could make visible flocs at the desired 50 mL/s flow rate, a new flocculator would not be needed. The High Rate Sedimentation - Plate Settlers team tried to make flocs with this flocculator at a flow rate of 50 mL/s, but no visible flocs were formed. High velocities through the flocculator resulted in a high energy dissipation rate and broke flocs as they collided at high speeds. Water traveled through the flocculator too quickly, which also correlated to a shorter residence time and lower collision potential.

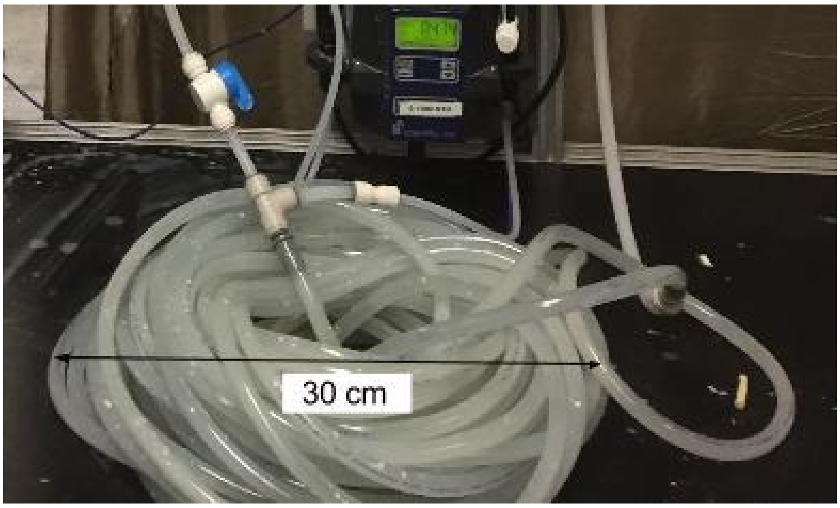
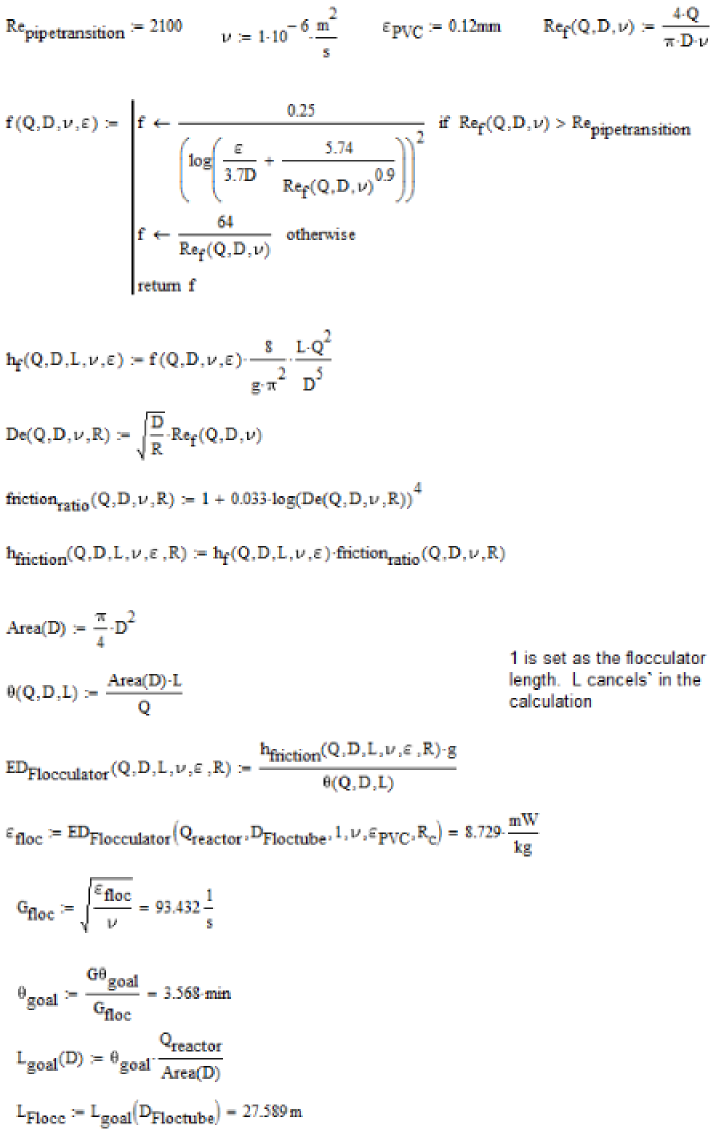


Figure 5: The Fall 2015 High Rate Sedimentation team used a tube flocculator that was made with 0.95 cm (3/8 in) flexible tubing and coiled into a 30 cm diameter circle.

Energy dissipation is a measurement of kinetic energy in the flocculator and an indicator of the size of flocs leaving the flocculator. An energy dissipation rate between 5 and 10 mW/kg was used because that would allow adequate collisions while preventing floc break-up. Calculations were made using previous equations as shown in Figure 6 from AguaClara member Casey Garland. The equations required three inputs (tubing diameter, coiling diameter, and flow rate) and returned the required tubing length and energy dissipation rate . Balancing and modifying the three inputs were critical to achieving the desired energy dissipation rate and a flocculator length that could fit on the lab bench.



$$Re_{pipetransition} := 2100 \qquad \nu := 1\cdot10^{-6}\cdot\frac{m^2}{s} \qquad \varepsilon_{PVC} := 0.12mm \qquad Re_f(Q,D,\nu) := \frac{4\cdot Q}{\pi\cdot D\cdot\nu}$$

$$f(Q,D,\nu,\varepsilon) := \left| \begin{array}{l} f \leftarrow \dfrac{0.25}{\left(\log\left(\dfrac{\varepsilon}{3.7D} + \dfrac{5.74}{Re_f(Q,D,\nu)^{0.9}}\right)\right)^2} \quad \text{if } Re_f(Q,D,\nu) > Re_{pipetransition} \\ f \leftarrow \dfrac{64}{Re_f(Q,D,\nu)} \quad \text{otherwise} \\ \text{return } f \end{array} \right.$$

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

$$De(Q,D,\nu,R) := \sqrt{\frac{D}{R}}\cdot Re_f(Q,D,\nu)$$

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

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

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

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

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

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

$$\varepsilon_{floc} := ED_{Flocculator}\left(Q_{reactor}, D_{Floctube}, 1, \nu, \varepsilon_{PVC}, R_c\right) = 8.729\cdot\frac{mW}{kg}$$

$$G_{floc} := \sqrt{\frac{\varepsilon_{floc}}{\nu}} = 93.432\,\frac{1}{s}$$

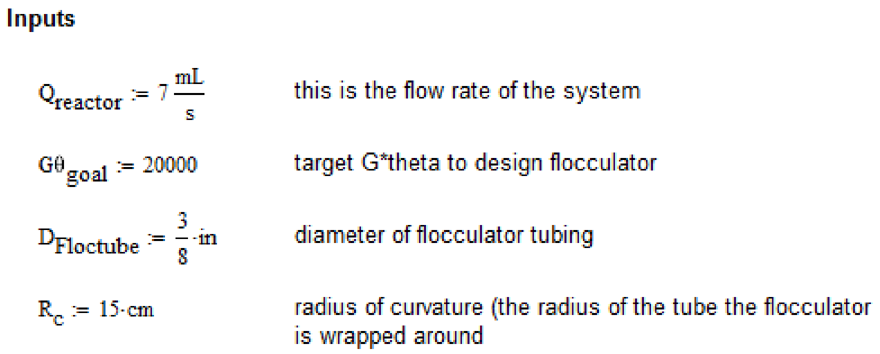
$$\theta_{goal} := \frac{G\theta_{goal}}{G_{floc}} = 3.568\cdot min$$

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

$$L_{Flocc} := L_{goal}\left(D_{Floctube}\right) = 27.589\,m$$

Figure 6: Equations were used to calculate the energy dissipation rate (ϵ .floc) and the required length of the flocculator L.Floc to achieve this ϵ .floc and L.Floc. Based on these equations, the required length of flocculator was 27.589 m.

The High Rate Sedimentation - Plate Settlers team first tested the viability of using an energy dissipation rate of 5 to 10 mW/kg. The existing diameter of flexible tubing was 0.95 cm (3/8 in) and it was coiled with a diameter of 30 cm. These inputs were used to calculate the flow rate that would give a energy dissipation rate between 5 to 10 mW/kg. The flocculator design equations returned that a flow rate of 7 mL/s would provide effective flocculation for the current flocculator design. The apparatus was operated at the 7 mL/s flow rate and easily visible flocs formed. This test shows that the equations can be used to accurately predict specifications for an effective flocculator for the larger 50 mL/s flow rate.



Inputs

$Q_{reactor} := 7\frac{mL}{s}$	this is the flow rate of the system
$G\theta_{goal} := 20000$	target G*theta to design flocculator
$D_{Floctube} := \frac{3}{8}\cdot in$	diameter of flocculator tubing
$R_c := 15\cdot cm$	radius of curvature (the radius of the tube the flocculator is wrapped around

Figure 7: Inputs for the flocculator calculation of the first apparatus.

At a flow rate of 7 mL/s, the energy dissipation rate of the 0.95 cm (3/8 in) diameter tube flocculator was 8.729 mW/kg. The length of the flocculator needed was 27.589 m (90.5 ft), which made the residence time 98 seconds.

Pump and Stock Solutions

A 6-600 RPM pump with two heads and size 18 peristaltic tubing was used to supply tap water at 7 mL/s. Two pump heads were added to the 6-600 RPM pump because one head did not supply enough flow when the 50 mL/s flow rate was tested. Two separate 1-100 RPM pumps were used for coagulant and clay to allow for flexibility in changing the two flows separately. The influent turbidity was set to 100 NTU or 0.17 g/L clay concentration inside the flocculator to create sufficient flocs for observation. A 6-liter container of 7 g/L clay stock solution was kept in suspension during the experiment with a mixer. At a total flow rate of 7 mL/s, the clay stock solution was pumped at 0.17 mL/s to obtain a 0.17 g/L influent clay water concentration, as demonstrated in Figure 8. A 1-100 rotations per minute(RPM) pump with size 14 peristaltic tubing set at 48 RPM provided this flow rate.

$$Q_{floc} := 7\,\frac{mL}{s}$$

$$C_{clay} := 100NTU = 0.17\cdot\frac{gm}{L}$$

$$C_{stockclay} := 7\,\frac{gm}{L}$$

$$Q_{clayinput} := \frac{C_{clay}\cdot Q_{floc}}{C_{stockclay}} = 0.17\,\frac{mL}{s}$$

Figure 8: Equations used to calculate the influent clay water concentration in the flocculator, and the flow rate of the clay stock solution needed to be pumped. Q.floc is the total flow rate; C.clay is the influent clay water concentration; C.stockclay is the clay stock solution concentration; Q.clayinput is the flow rate of the clay stock solution needed to be pumped. The same set of equations was also used to calculate the flow rate of coagulant.

The Fall 2015 High Rate Sedimentation team determined that 1.5 mg/L coagulant worked most efficiently for floc formation of 100 NTU clay water, so the same concentration was used for this semester. In the stock solution, 3.125 mL of 69.4 g/L concentration polyaluminum chloride (PACl) was added to 1 L of water. With a 216.9 mg/L stock solution, coagulant needed to be pumped at 0.048 mL/s to achieve the desired 1.5 mg/L mixed concentration. A 1-100 RPM pump with size 13 peristaltic tubing set at 48 RPM would achieve the desired flow rate. The full setup is shown in Figure 10.

After the flow rate of the clay suspension and coagulant solutions were designed, the flow rate of the necessary tap water was calculated to be 6.78 mL/s based on the flow rate of clay and coagulant solutions.

Tubing Connections

Tap lines were connected to pumps, flocculator, and sedimentation tube using 0.95 cm (3/8 in) rigid tubing and clay stock solutions were connected using microtubing to achieve a higher velocity and prevent settling.

The High Rate Sedimentation - Plate Settlers team then ran water through the apparatus and found that almost no water was entering the turbidimeter and the NTU readings were incorrect. This occurred because the flow path of least resistance was through the flocculator, not the turbidimeter. The team added a manual valve to the tubing connected to the flocculator so that when the team wanted to get a reading, the valve could be closed to force water into the turbidimeter. Size 0.64 cm (1/4 in) rigid tubing was used to connect the clay and coagulant dosed water to the turbidimeter.

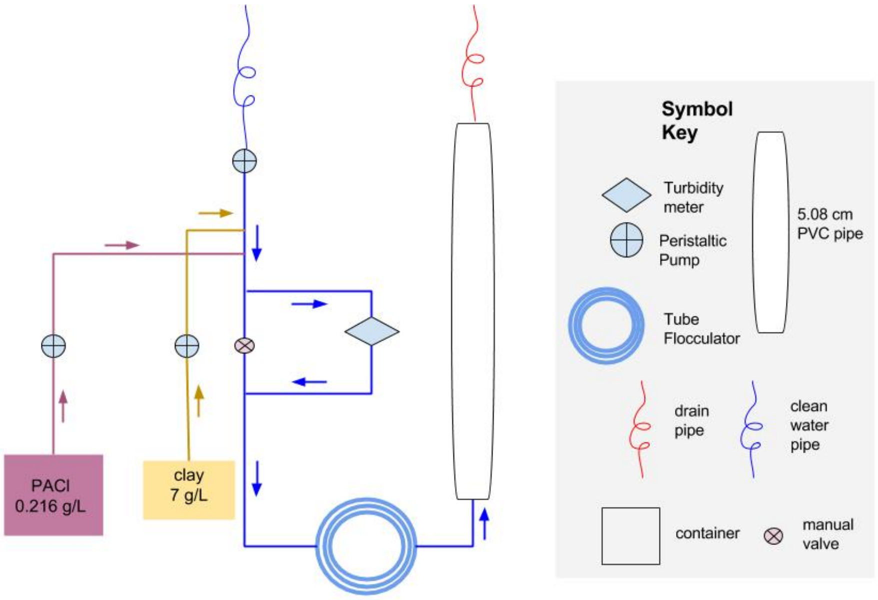


Figure 9: The schematic shows that water passes through a 6-600 RPM pump; coagulant and clay stock solutions pass through separate 1-100 RPM pumps. The coagulant and clay stock solutions are rapidly mixed with the water through a tee-connector. When the manual valve is closed, the rapidly-mixed water enters a turbidimeter and then the tube flocculator. When the manual valve is open, the majority of the rapidly-mixed water bypasses the turbidimeter and enters straight into the tube flocculator.

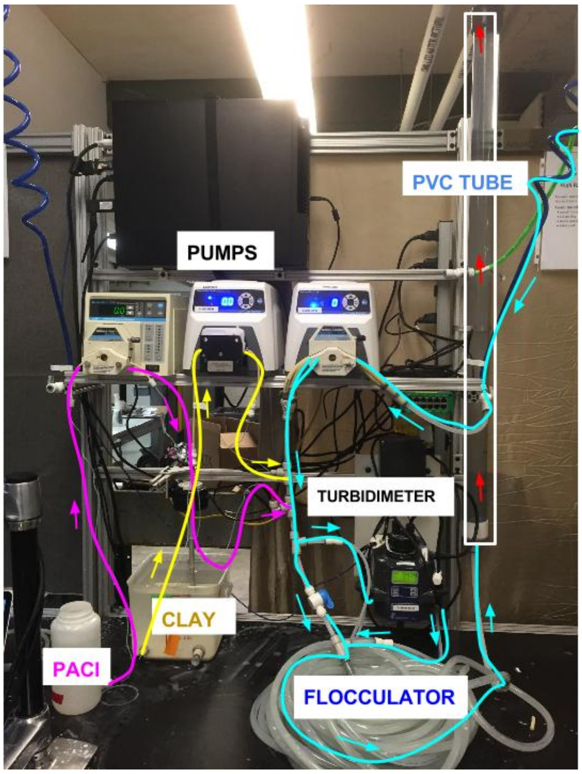


Figure 10: The arrows show the direction of water flow through the sedimentation tank system and flocculator. Flow paths follow the same direction as shown in Figure 9.

Analysis

Testing showed that a new and larger flocculator was necessary to build an apparatus capable of operating at a flow rate of 50 mL/s. The 0.95 cm (3/8 in) flocculator did not produce flocs at a 50 mL/s flow rate because the energy dissipation rate inside the flocculator was too high. This issue was solved when the flow and energy dissipation rate were lowered. Successful floc formation in the smaller flocculator (shown in Figure 11) proved that a larger flocculator designed using the same energy dissipation rate formed flocs.

Figure 11: Flocs passing through the PVC pipe sedimentation tube are large enough to see with the naked eye, thus proving that the flocculator design equations are valid for high flow rates.

Figure Eight Flocculator

Experimental Apparatus Design

The tube flocculator was redesigned to promote floc formation for the lab-scale sedimentation tank at a flow rate of 50 mL/s. Larger tubing was needed to satisfy the energy dissipation constraint of 5-10 mW/kg for the larger flow rate.

Flocculator Design

Designing the larger flocculator required manipulating input values using the same set of equations shown in Figure 6. From the equations, the High Rate Sedimentation - Plate Settlers team concluded that 2.2 cm (7/8 in) inner diameter flexible tubing would satisfy the desired 50 mL/s flow rate while keeping the energy dissipation rate between 5 - 10 mW/kg. The tubing was coiled in the same circular design as that of the smaller flocculator developed by the Fall 2015 HRS team. The 27.6 m long 2.2 cm (7/8 in) inner diameter tubing was coiled to a diameter of 40 cm to fit on the lab bench. Using the flocculator design equations, the team determined the energy dissipation rate to be 8.729 mW/kg.

When the apparatus was operated, large flocs started settling quickly on the walls of the flocculator tubing shown in Figure 12. The stagnation of flocs could be solved by winding the tubing into a figure eight shape around two 15.2 cm (6 in) pipes, as shown in Figure 13. The figure eight shape encourages circulation at the bends of the shape, which prevents flocs from settling onto the walls of the flocculator.After the modification of design,the High Rate Sedimentation - Plate Settlers team managed to remove the air pockets inside the tubing by positioning the tubing vertically as Figure 14 shows, and injecting water from the bottom of the tubing to the top. Air was forced to move up by pressure and eventually exited from the top. The flocculator was then returned to its horizontal position and connected to pumps and stock solutions.

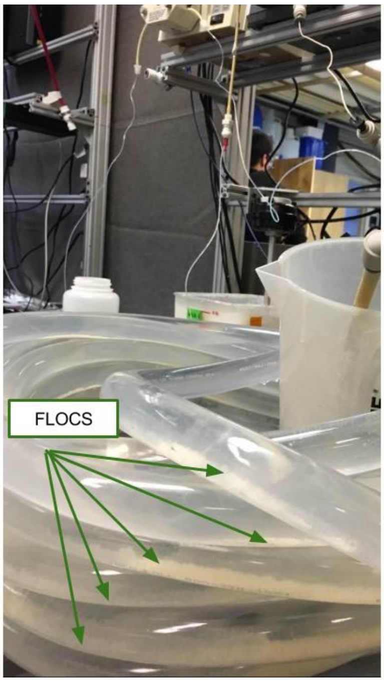


Figure 12: Flocs settled down within the larger flocculator.

Figure 13: Tubing was wrapped around two PVC pipes to maintain the flocculator a figure eight shape.

Flocculator Orientation

The flocculator was oriented vertically (see Figure 14) in order to remove air pockets that were inside of the flocculator. After water was run through the system and air pockets were removed, the flocculator was oriented back horizontally as shown in Figure 13 for improved flocculation.

Figure 14: Water was injected from the bottom to push air up to the top and eventually remove air inside the tubing completely. Air pockets were easily removed when the flocculator is oriented in the vertical position.

The projected plan-view area of the vertically-oriented flocculator is larger than that of the horizontally-oriented flocculator. Projected plan-view area is a measure of flat surfaces for flocs to settle on. In the vertical orientation, the flocculator tubing is mostly horizontal, so a majority of flocs settled onto the walls of the flocculator instead of moving forward into the sedimentation tank. Consequently, a horizontally oriented flocculator would transport a more consistent inflow of flocs to the sedimentation tank.

Modifications to Apparatus

Since the flow rate of the water input was increased from 7 mL/s to 50 mL/s, the 6-600 RPM tap water pump was also increased to 393 RPM. Clay and coagulant stock solution concentrations were increased so the influent concentrations remained 0.17 g/L and 1.5 mg/L for clay and coagulant, respectively. The clay stock solution concentration was increased from 7 mg/L to 50 mg/L, and the coagulant stock solution concentration was increased to from 0.216 g/L to 1.55 g/L.

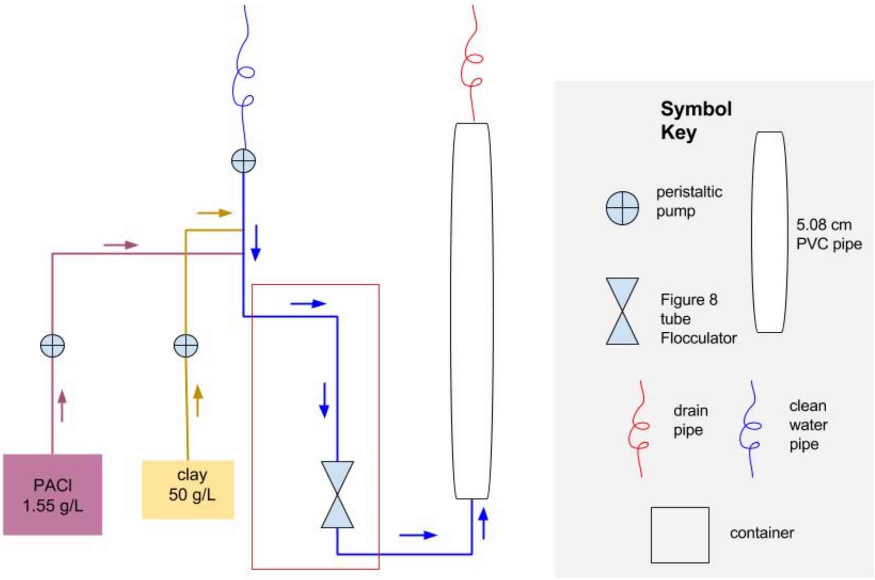


Figure 15: Tap water passes through a 6-600 RPM pump. Coagulant and clay stock solutions pass through separate 1-100 RPM pumps. The coagulant and clay stock solutions rapidly mix with the water through a tee-connector. The rapidly-mixed water goes straight into the figure-eight shaped tube flocculator. The water then enters the PVC pipe sedimentation tube and leaves through the disposal line. The red box indicates the changes made to the apparatus.

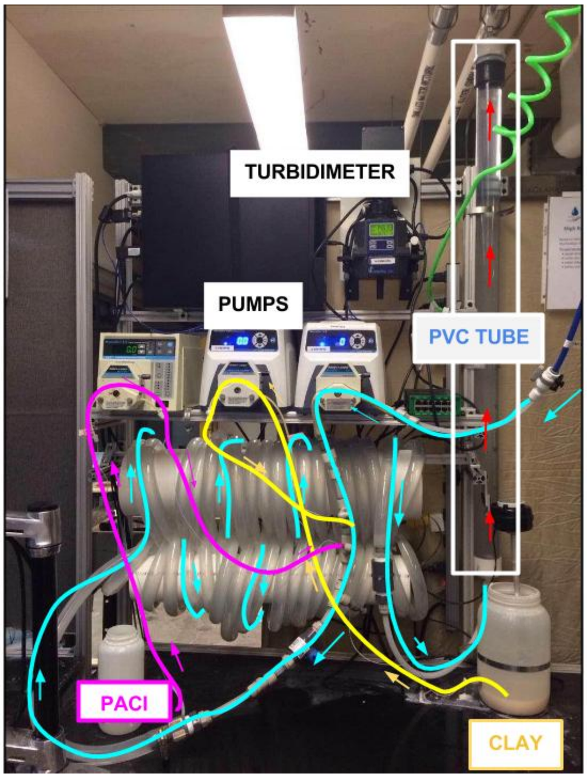


Figure 16: Arrows trace the path of the water as it runs through the apparatus. The direction of flow follows the same paths and direction as shown in Figure 15.

Analysis

A larger flocculator was the solution for creating visible flocs at the higher 50 mL/s flow rate. Despite initial obstacles with flocs settling in the flocculator, the new flocculator eventually created large and dense flocs that continuously entered the sedimentation tank. The figure eight shape coiling was the critical step in resolving the problem of flocs settling.

Sedimentation Tank and Plate Settlers

The High Rate Sedimentation - Plate Settlers team started constructing their own sedimentation tank design while conducting experiments with the sedimentation tank of the High Rate Sedimentation - Floc Blanket team to maximize progress.

Sedimentation Tank Design

PVC welding was shown to be unpredictable and difficult to achieve water tight connections. Consequently, the High Rate Sedimentation-Plate Settlers team designed their tank with PVC glue connections.

In order to achieve water tight connections, the High Rate Sedimentation-Plate Settlers team glued square 0.95 cm wide keystock rods to edges connecting the sides of the tank. All sides of the tank were constructed using 0.95 cm thick clear PVC sheeting, except for the base of the tank which was constructed with an opaque PVC sheet. As seen in Figure 17, the tank was 70 cm tall, 23.81 cm long, and 5 cm wide, with a 23.81 cm by 12 cm base to stabilize the tank. Keystock was glued to the edges connecting the fronts and sides of the tank, and to the edges connecting the base and fronts of the tank.

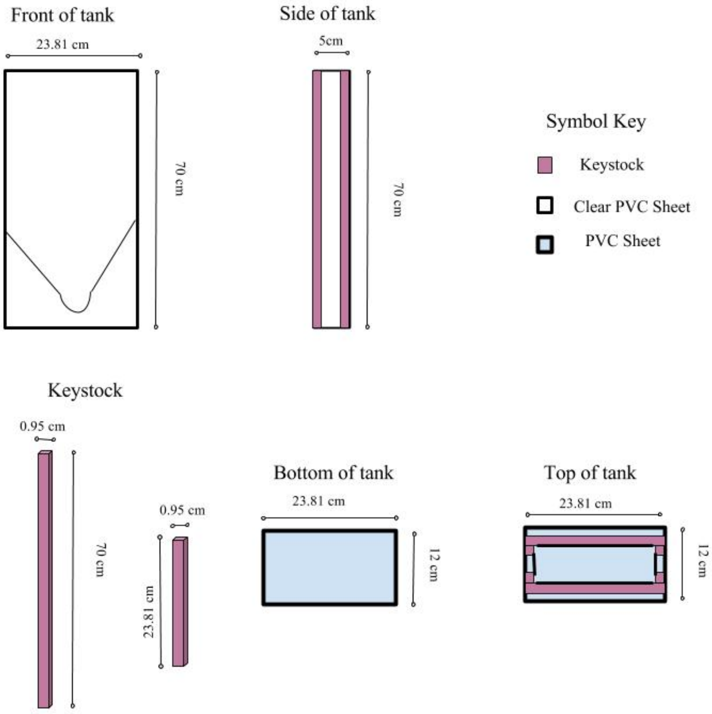


Figure 17: Shown above are the pieces that will be used to assemble the sedimentation tank. Each piece was designed so there was an extra 0.95 cm strip to account for edges where glue would be applied.

While the High Rate Sedimentation-Plate Settlers tank had the same dimensions as the High Rate Sedimentation-Floc Blanket tank, it did not have a weir and had two sloped bottoms rather than one. The High Rate Sedimentation-Plate Settlers team required space above the sloped bottom to insert plate settlers and conduct experiments with plate settler geometries. As shown in Figure 18, a one-sloped bottom leaves less space at the top of the tank for plate settlers than a two-sloped bottom does. Therefore, the High Rate Sedimentation-Plate Settlers team decided to include two sloped bottoms rather than just one.

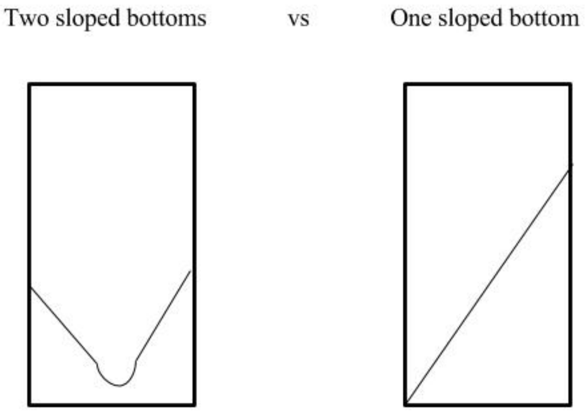


Figure 18: The difference between the amount of space taken up in the tank with two sloped bottoms and with one sloped bottom.

The High Rate Sedimentation-Plate Settlers tank also included a jet reverser. The jet reverser was made by heating a 2.54 cm (1 in) PVC pipe and molding one end into the shape of a narrow rectangle. As shown in Figure 19, water enters through a coupling that is attached to the wall of the tank, which forces the water to exit through a PVC jet reverser. A curved bottom in between the two sloped bottoms reverses the direction of the influent water jet.

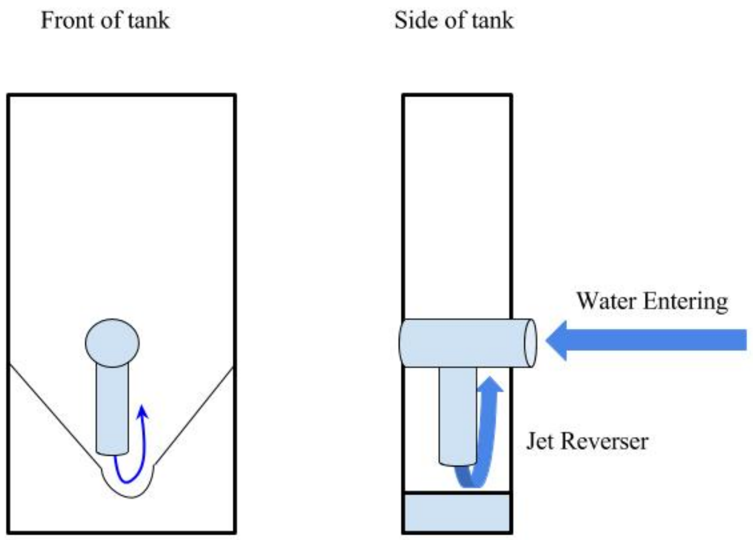
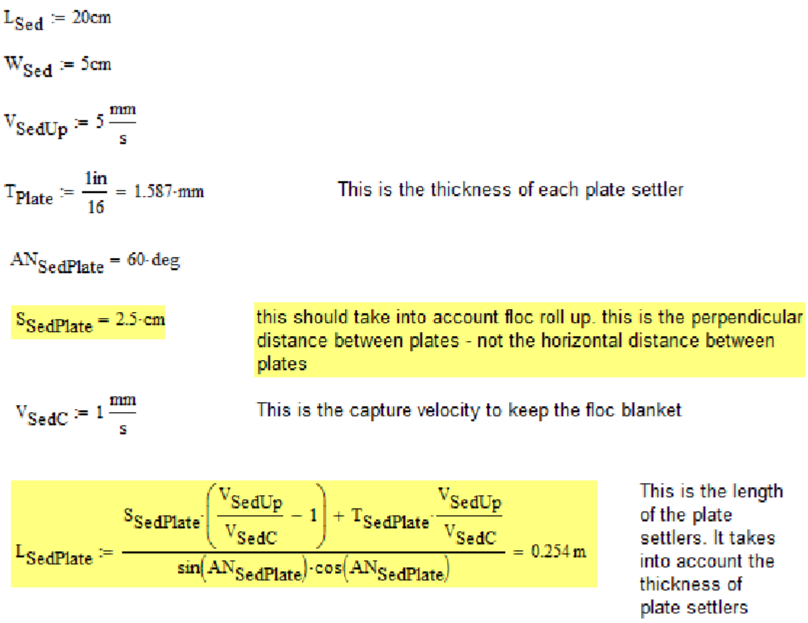


Figure 19: Pictured is the design for the High Rate Sedimentation-Plate Settlers sedimentation tank. Water enters through a coupling and then exits through a PVC jet reverser. The curved bottom reverses the direction of the influent water jet as shown in the schematic.

Floc Blanket Stabilizers Design

The High Rate Sedimentation - Plate Settlers team used 1.587 mm (1/16 in) thick polyvinyl chloride (PVC) sheets as plate settlers. This set of plate settlers was added to stabilize the floc blanket, and they will be referred to as floc blanket stabilizers. The floc blanket stabilizers were designed to be at a 60°, the angle where flocs were found to slide down the plate and into the floc blanket most effectively (Anyene et al., 2015). The perpendicular distance between each plate settler was set to 2.5 cm to maximize projected horizontal settling area while avoiding floc roll-up. When the distance between plates is too narrow, a high velocity gradient between each plate forms and flocs roll up the plates and out through the top(Weber-Shirk, 2015). The designed capture velocity was 1 mm/s, which in theory should capture flocs that would have been suspended at the 1 mm/s upflow velocity. These flocs then slide down the floc blanket stabilizer plates back into the floc blanket. The length of floc blanket stabilizers were calculated to be 0.254 m, as shown in Figure 21.



$L_{Sed} := 20\text{cm}$

$W_{Sed} := 5\text{cm}$

$V_{SedUp} := 5\frac{\text{mm}}{\text{s}}$

$T_{Plate} := \frac{1\text{in}}{16} = 1.587\cdot\text{mm}$ This is the thickness of each plate settler

$AN_{SedPlate} = 60\cdot\text{deg}$

$S_{SedPlate} = 2.5\cdot\text{cm}$ this should take into account floc roll up. this is the perpendicular distance between plates - not the horizontal distance between plates

$V_{SedC} := 1\frac{\text{mm}}{\text{s}}$ This is the capture velocity to keep the floc blanket

$$L_{SedPlate} := \frac{S_{SedPlate}\cdot\left(\frac{V_{SedUp}}{V_{SedC}} - 1\right) + T_{SedPlate}\cdot\frac{V_{SedUp}}{V_{SedC}}}{\sin\left(AN_{SedPlate}\right)\cdot\cos\left(AN_{SedPlate}\right)} = 0.254\,\text{m}$$

This is the length of the plate settlers. It takes into account the thickness of plate settlers

Figure 20: These inputs and equations were used to calculate the length of plate settlers, which was 0.254 m

Experimentation with Plate Settlers

At upflow velocities as high as 5 mm/s, floc blanket stabilizer plates can capture flocs and recycle them back into the floc blanket. Since the new sedimentation tank was still in the process of fabrication, the High Rate Sedimentation - Plate Settlers team started experimentation with the High Rate Sedimentation - Floc Blanket team. Floc blanket stabilizers were inserted into the sedimentation tank as shown in Figure 21, and a concentrated floc blanket was formed at the bottom of the tank (Figure 21). In all experiments, water was drawn by a peristaltic pump through a tube settler to mimic the traditional set of plate settlers that are usually at the top of the sedimentation tank.

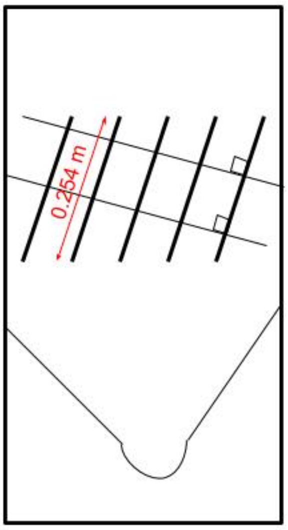


Figure 21: The plate settlers are slanted at a 60°angle with two thin, threaded nylon rods connecting them at a 90°angle.

Floc Blanket Stabilizers Plate Selection

Recycling flocs back into the floc blanket using plate settlers is a novel idea that does not have any literature to support its effectiveness. At the brainstorming stages, the High Rate Sedimentation - Plate Settlers team determined that the most effective plate settlers would produce the most dense floc blanket. Two plate geometry ideas suggested by Professor Monroe Weber-Shirk were continuous and porous plates. Continuous plate and porous plate floc blanket stabilizers have the same length and width (calculations for these dimensions were explained in a previous section), but porous plates have holes drilled into them. The idea behind porous plates was that these extra pores would stimulate more mixing as water passed through them.

Experimentation at 3 mm/s and 4 mm/s Upflow Velocities

Continuous plates and porous plates were both tested at 3 mm/s upflow velocity, and the influent turbidity for both trials was set to 100 NTU.

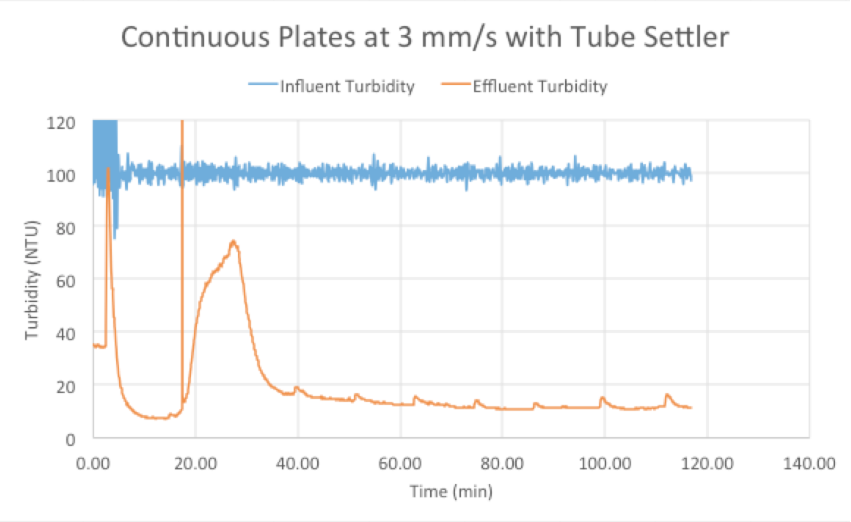


Figure 22: At a 3 mm/s upflow velocity, the trial with continuous plates produced an average effluent turbidity of 17.8 NTU.

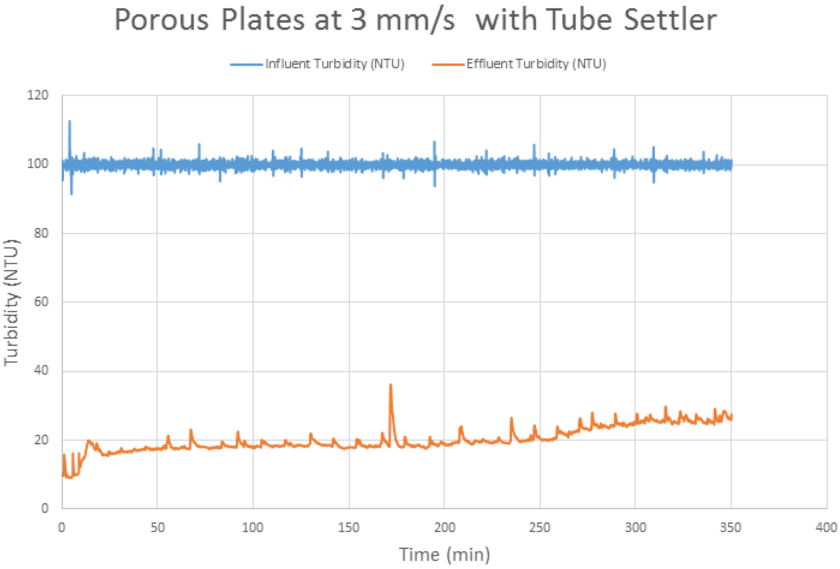


Figure 23: At a 3 mm/s upflow velocity, the trial with porous plates produced an average effluent turbidity of 20.2 NTU.

Continuous plates and porous plates were both tested at 4 mm/s upflow velocity. However, the High Rate Sedimentation - Plate Settlers team added a trial without any floc blanket stabilizers as a baseline comparison. The influent turbidity was still kept at 100 NTU for the experiment with no floc blanket stabilizers and the experiment with continuous plates. However, the experiment with porous plates was mistakenly conducted with an influent turbidity of 41.5

NTU. Therefore, it is necessary to use percent removal for comparison.

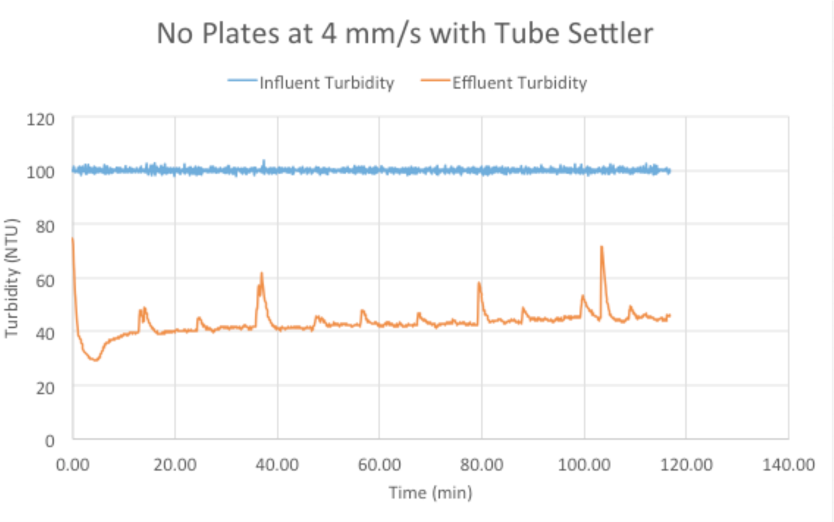


Figure 24: At a 4 mm/s upflow velocity, the trial with no added floc blanket stabilizers produced an average effluent turbidity of 43.7 NTU.

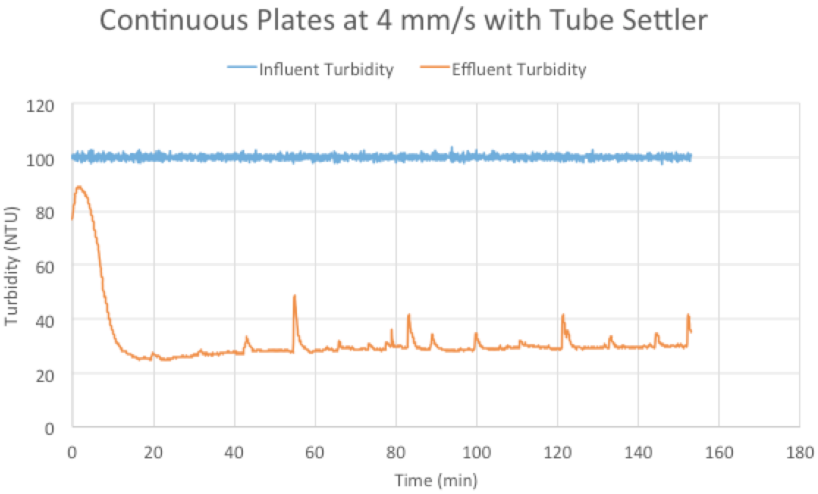


Figure 25: At a 4 mm/s upflow velocity, the trial with continuous plates produced an average effluent turbidity of 29.3 NTU.

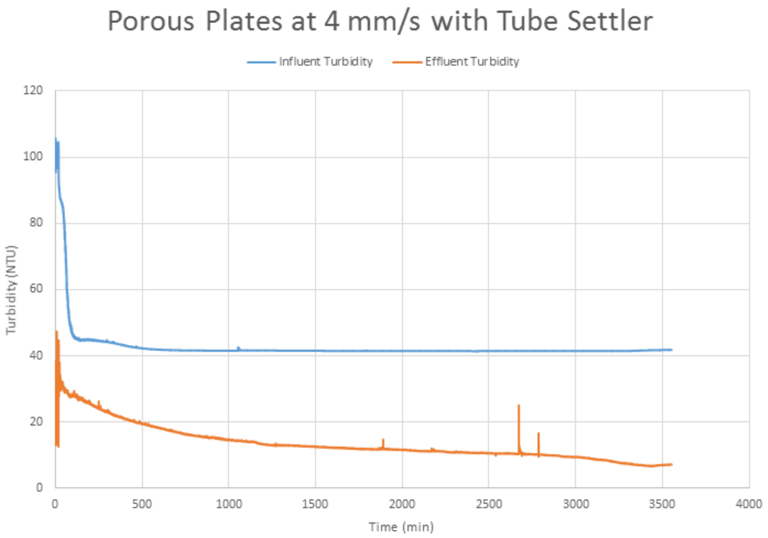


Figure 26: At a 4 mm/s upflow velocity, the trial with porous plates produced an average effluent turbidity of 11.2 NTU.

Table 1: Summary of Experimentation Trial Results

Date	Plate Type	Upflow Velocity	Influent Turb	Effluent Turb	% Removal
4/28/16	Continuous	3 mm/s	100 NTU	17.8 NTU	82.2%
4/28/16	Porous	3 mm/s	100 NTU	20.2 NTU	79.8%
5/3/16	None	4 mm/s	100 NTU	43.7 NTU	56.3%
5/3/16	Continuous	4 mm/s	100 NTU	29.3 NTU	70.7%
5/11/16	Porous	4 mm/s	41.5 NTU	11.2 NTU	73.0%

Analysis

Water that exited from the top of the sedimentation tank was less turbid than the influent, but still had a considerable amount of flocs that exited.

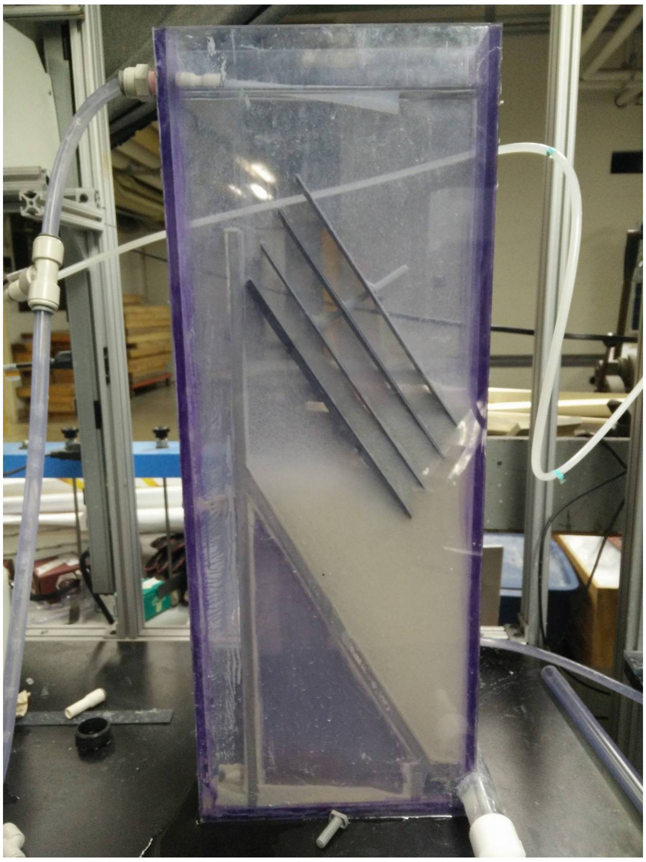


Figure 27: The floc blanket stabilizers concentrated the floc blanket so that there was an apparent difference in density above and below the plates. As flocs slid down the plates, they would fall back into the floc blanket to be resuspended by the jet reverser. A distinct boundary appeared where the flocs became more concentrated at the bottom of the floc blanket stabilizers.

Steady-state conditions at both 3 mm/s and 4 mm/s upflow velocities displayed a clear interface where the floc blanket was concentrated. As shown in Figure 27, the floc blanket was concentrated up until the bottom of the floc stabilizers.

The effluent turbidity results were only slightly different between the continuous stabilizers and the porous stabilizers. Additionally, there were conflicting results from experimentation at 3 mm/s and at 4 mm/s. At 3 mm/s, continuous plates (82.2 % removal) performed slightly better than porous plates (79.8 % removal). However, at 4 mm/s, porous plates (73.0 % removal) performed slightly better than continuous plates (70.7 % removal). Thus, there is no clear evidence of which plate geometry is more effective in aiding particle removal during sedimentation.

Despite inconclusive plate geometry testing, there is strong evidence that the addition of plates does aid in particle removal. In contrast to the trials with various plates, the trial with no floc blanket stabilizers had a drastic increase in effluent turbidity. From this, it can be concluded that the addition of plates as floc blanket stabilizers is effective in both concentrating the floc blanket and reducing the effluent turbidity.

Conclusions

The research done this semester has proved that the addition of plates in the floc blanket can effectively concentrate the floc blanket at upflow velocities as high as 4 mm/s. Though no solid conclusion could be drawn about the effectiveness of each plate geometry, it was determined that the addition of floc blanket stabilizing plates improves the removal efficiency of the sedimentation tank.

Since the current AguaClara design operates at 1 mm/s without floc blanket stabilizers, the addition of these plates would allow operation at higher upflow velocities with similar performance. Efficiency at higher velocities opens the door to the possibility of smaller sedimentation tanks, and therefore more cost-effective treatment plants. As further research is done on high rate sedimentation, more communities will be able to have access to sustainable drinking water treatment plants.

Future Work

In the coming semesters, there are many modifications that need to be made to ensure unbiased results and reliable data. For instance, it is crucial that the apparatus is started and stopped using a standard set of operating procedures to avoid operational bias.

Imminent next steps of testing include running three types (no plates, continuous plates, porous plates) of tests for more upflow velocities between 1 and 5 mm/s. Moreover, repeated trials are necessary to make concrete conclusions when two variables deliver similar results.

From a broader point of view, progress toward improving high rate sedimentation requires focusing on the quality of the floc blanket formed in each scenario. Important characteristics to quantify are floc size, floc density, floc shape, and the resulting floc blanket density. If the previously mentioned attributes can be easily quantified, it would allow researchers to more directly approach the issue of creating efficient sedimentation tanks even at high upflow velocities.

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Weber-Shirk, M. (2015). Sedimentation.

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Semester Schedule

Task Map

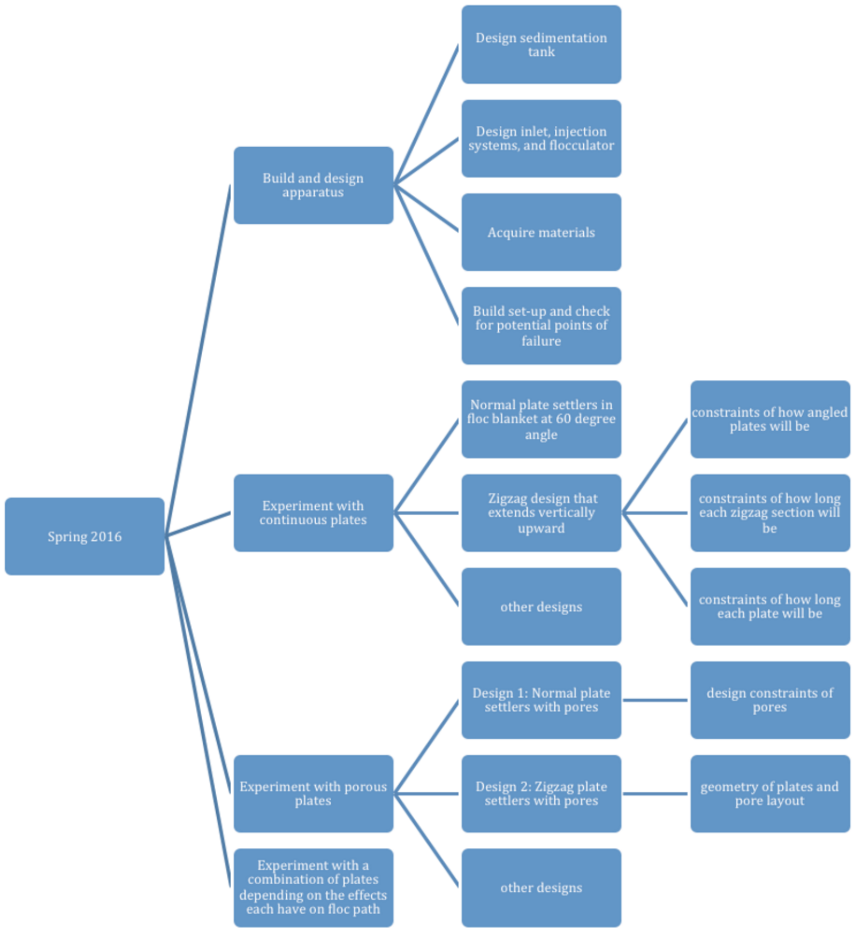

Figure 28: High Rate Sedimentation - Plate Settlers Spring 2016 Task Map

Task List

1. Build and design sedimentation tank and flocculator/Mar. 16 - Yuqi
    (a) Design sedimentation tank (Floc Blanket team) **completed**
        i. PVC welding proved to be time consuming and difficult, so the HRS-Plate Settlers team decided to make the tank using glued joints.
    (b) Design inlet, injection systems, and flocculator **completed**
        i. Test flocculator from previous semester (did not work) **completed**

        ii. Design new flocculator with 2.2 cm (7/8 in) tubing (works after coiled in a figure eight and vertically oriented). **completed**
    (c) Acquire materials for sedimentation tank and flocculator **completed**
    (d) Build setup and check for potential points of failure **completed**

2. Experiment with continuous plates/May 14- Lishan
    (a) Design 1: Normal plate settlers in floc blanket at 60°angle **completed**
    (b) Design 2: Zigzag design that extends vertically upward **completed**
        i. Figure out constraints of how angled plates will be **completed**
        ii. Figure out constraints of how long each zigzag section will be **completed**
        iii. Figure out constraints of how long each plate will be **completed**
    (c) other designs **completed**

3. Experiment with porous plates/May 14- Sidney
    (a) Design 1: Normal plate settlers with pores **completed**
        i. Figure out design constraints of pores **completed**

Report Proofreader: Lishan Zhu