Sedimentation Tank Hydraulics Final Research Report

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Part I

Literature Review

In preparation for our experiments to test for optimum sedimentation tank geometry, previous literature was reviewed. Matt Hurst's paper, "Parameters affecting steady-state floc blanket performance," gave us insight into the parameters affecting floc blanket performance including energy dissipation rate in both the flocculator and the floc blanket, upflow velocity, the height and solids concentration of the floc blanket, and coagulant dosage. Hurst, 2010 found the optimal upflow velocity to be 1.0 mm/s for a turbidity of 100 NTU using a relatively high dose (45 mg/L) of alum. [2]. Our experiments will be conducted at this influent turbidity, but we will be using an upflow velocity of 1.2 mm/s, as this is most commonly used in AguaClara facilities in Honduras. Hurst also writes that an increase in energy dissipation rate may increase flocculator performance, which in turn could increase performance of the floc blanket. This semester, we will not be exploring this point further, but instead will look at the effect of increased flocculator residence time on floc blanket performance. We will lengthen the flocculator by about 8 times the original length to increase the residence time and increase the number of collisions between particles. Hurst's flocculator included 16 meters of tubing, 12.5 meters of which was coiled. We used 122 meters of tubing in a figure-eight pattern rather than the short length of tight coils used previously. The previous constant curvature of the flocculator created a uniform circulation pattern that concentrates flocs near the centers of the circulation zones that develop in curved tubing. The figure-eight pattern causes the secondary circulation to reverse direction, thus increasing mixing under laminar flow conditions (Reynolds number calculated to be 815). See calculations for the Reynolds number below: (1)

Reynolds Number Calculation

$$dfloc := \frac{3}{8} in$$

$$Q_{reactor} = 365.76 \cdot \frac{mL}{min} \qquad \nu = 1 \times 10^{-6} \frac{m^2}{s}$$

$$AreaPipe := \pi \left(\frac{dfloc}{2}\right)^2 = 0.11 \cdot in^2 \qquad PerimeterPipe := \pi \cdot dfloc = 1.178 \cdot in$$

$$Vpipe := \frac{Q_{reactor}}{AreaPipe} = 0.086 \frac{m}{s}$$

$$Dhydraulic := \frac{4 \cdot AreaPipe}{PerimeterPipe} = 0.375 \cdot in$$

Hydraulic diameter equals actual diameter since tube is flowing full

$$RePipe := \frac{Vpipe \cdot Dhydraulic}{\nu} = 814.873$$

Figure 1: Reynolds Number Calculations

One of our first objectives was to switch from alum (aluminum sulfate) to PACl (polyaluminum chloride), as it is less expensive and more widely used by AguaClara facilities in Honduras. After reviewing the PACl dosage used in the Atima plant, we determined that for 100 NTU influent turbidity, we would test coagulant dosages from 5 to 15 mg/L in steps of 5 mg/L. Testing these values while monitoring overall sedimentation tank performance will allow us to determine optimal PACl dosage at 100 NTU. According to Figure 10 of Hurst, 2010 , increasing alum dose leads to increased performance (lower effluent turbidity) up to a certain point, after which, performance levels out.

Hurst, 2010 found that particle removal (referred to as pC* in Figure 12), was linear with blanket height up until about 55 cm, after which pC* leveled out. Previous sedimentation tank hydraulics teams have used 60 cm as a constant height for the floc blanket, however, we will use a height of 85 cm throughout our experiments. Increasing the height of the weir will allow us to test a greater range of floc hopper depths while still being a sufficient distance away from the tube settlers (15 cm). Our experiments will be performed with the floc blanket at steady-state, which as noted in previous team's reports, formed in about two to three hours at 100 NTU influent turbidity. According to Hurst, 2010, the energy dissipation rate in the floc blanket is related to solids concentration. This is because the head loss through a fluidized bed is due to the difference in density between the fluidized bed and the density of the incoming fluid. As the solids concentration in the floc blanket increases, the density increases and thus, the head loss and energy dissipation rate in the bed increase.

In addition, we wish to explore the energy dissipation rate in the jet that delivers flocculated water to the sedimentation tank and its effect on overall floc blanket performance. An increased energy dissipation rate would generate smaller flocs, and we hypothesize that this could ultimately improve the efficiency of the floc blanket. In order to increase the energy dissipation rate, we will increase jet velocity. This increased velocity also will allow the jet to entrain more of the floc blanket fluid and break up more of the larger flocs as they are entrained by the jet. With a larger number of small flocs and decreased floc size, we hypothesize that we will see improvement in colloid capture within the blanket.

Emeritus Professor Richard Dick provided us with some insight on sludge consolidation within the floc hopper. Based on the amount of time the sludge would be in the floc hopper, he believes that only zone settling occurs (not compression settling). In order to find a limiting concentration for the sludge, Professor Dick referenced the batch flux curve approach (see photograph below:2) should yield an accurate representation. To use this approach, we would need to calculate the settling velocity in the floc hopper. He also believes that since the length of our model sedimentation tank is short (1/2"), the glass end walls will have an effect on the settling velocity and limiting concentration of the sludge.

To test his hypothesis, we collected a sample of our sludge and tested it for suspended solids concentration by filtering the sludge and drying it according to Standard Methods. We would also use some of the collected sludge to calculate settling velocities in various sized containers. By changing the geometry of the containers, we would be able to check if the sidewalls affect the settling velocity.

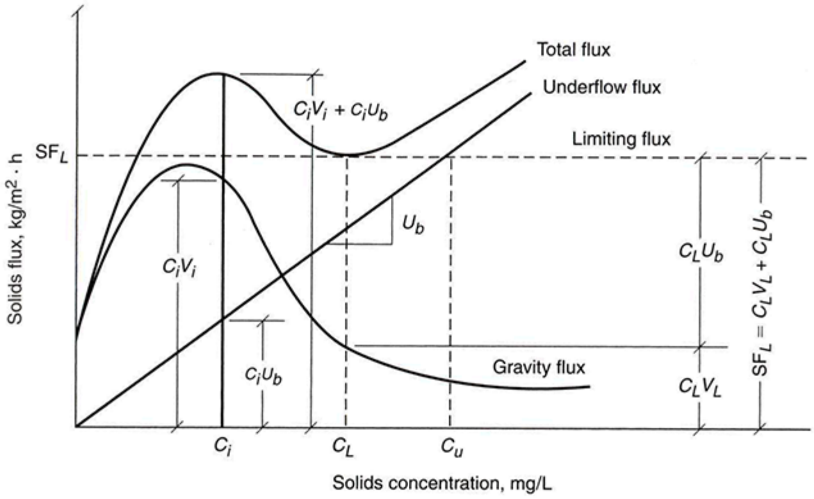


Figure 2: Batch Flux Curve [3]

Part II
Introduction

The sedimentation tank is used to form a floc blanket in the bottom of the tank and allow clean water to flow out the tube settlers at the top. The finished water turbidity coming out of the tube settlers needs to be below 5 NTU, as this is both the Honduran and Indian standard. Future AguaClara plants will include filters, which will decrease the effluent turbidity by a factor of 10. Thus, we can tolerate a higher effluent turbidity coming out of the tube settlers. The US standard is 0.3 NTU. We would prefer that the effluent water have the lowest possible NTU because a low effluent turbidity means that there are less particles in the effluent. As such, the particles do not pose as great of a hindrance to the chlorine's effects on disease-causing pathogens. We could probably achieve the 0.3 NTU level by making sure the tube settler effluent was below 3 NTU and then adding a filter.

Hurst, 2010 showed that increasing the depth of the floc blanket doesn't significantly affect performance after 50 cm, however this means that the filter analogy previously hypothesized to describe this area of particles may be invalid because filter performance generally increases with depth. Our current hypothesis is that floc blanket performance depends on floc size, not height. If our hypothesis holds true, a higher rate of production of small flocs will improve performance because large flocs in the floc blanket have a high surface shear that prohibits colloids from attaching. Small flocs are created in two ways; one being that flocs that have settled to the bottom of the tank are entrained in the high energy dissipation jet, causing further floc break-up. In addition, fluid from the sedimentation tank can be entrained by the jet, which causes floc break-up in the jet, itself. If the flocs become too small, they may not be captured in the floc blanket and instead leave through the tube settlers, which would increase the effluent turbidity.We wish to determine the energy dissipation rate that generates the small floc concentration in the blanket which optimizes floc blanket efficiency. We will do this by varying the inner diameter of the jet reverser to increase velocity and energy dissipation rate.

It is also possible that the floc break-up due to the jet reverser could be so great that the broken flocs are not caught by the blanket and move out through the tube settlers and into the effluent. We wish to create a greater concentration of small flocs while avoiding this failure mode. The following calculations show the influence of entrainment of fluid by the jet on the rate of small floc production.

The velocity of the centerline of a 2-D jet is given by (http://ceeserver.cee.cornell.edu/mw24/Archive/01/cee332/Lectures/09%20Jets_&_Plumes.ppt)

$$V_C = 2.41 V_{Jet} \sqrt{\frac{b_0}{s}} \tag{1}$$

where V_{Jet} is the velocity of the jet at the point of discharge, b_0 is the width of the jet, and s is the distance from the origin of the free jet. The round jet that discharges from the flocculator tube is expected to quickly flatten against the jet reverser and remain laminar as it flows around the jet reverser due to the stabilizing influence of the rapid acceleration around the bend. Thus entrainment of fluid from the floc blanket will begin in the section of the jet that is directly vertical upward. The energy dissipation rate in the jet decreases rapidly as the jet slows and grows in size. The thickness of a 2-D jet is given by

$$b = 0.116 s \tag{2}$$

The flow rate of a 2-D jet is given by

$$q = Vb \tag{3}$$

where q is the flow per unit length of the jet. Combining equations 1,2, and 3 we obtain an equation for the rate at which the flow rate of the jet increases as it entrains fluid

$$q = 0.28 V_{Jet} \sqrt{s b_0} \tag{4}$$

The initial jet width, b_0 can be estimated by assuming the round jet issuing from the flocculator spreads into a rectangular jet without significant entrainment of fluid.

$$b_0 = \frac{A_{Jet}}{L_{Tank}} = \frac{\pi D_{Jet}^2}{4 L_{Tank}} \tag{5}$$

The energy dissipation rate at the centerline of a 3-D jet is given by Baldyga et al. [1] as

$$\varepsilon_{Centerline} = \frac{50 D_{Jet}^3 V_{Jet}^3}{(x - 2D_{Jet})^4} \tag{6}$$

The minimum distance for which this relationship is valid is at $7D_{Jet}$. Under these conditions, equation 6 can be reduced to

$$\varepsilon_{MaxLocal} = \frac{(\Pi_{Jet} V_{JetLocal})^3}{D_{JetLocal}} \tag{7}$$

equation 7 can be used to estimate the energy dissipation rate 7 diameters ahead given the local velocity and jet diameter. The equations for jet velocity and for the energy dissipation rate can be combined to determine the distance from the jet at which the energy dissipation rate reaches a value that no longer provides significant floc breakup.

$$0.116s = \frac{\left(2.41\Pi_{Jet} V_{Jet} \sqrt{\frac{b_0}{s}}\right)^3}{\varepsilon_{MinBreakup}} \tag{8}$$

$$s = \left[\frac{\left(2.41\Pi_{Jet} V_{Jet} \sqrt{b_0}\right)^3}{0.116\varepsilon_{MinBreakup}}\right]^{\frac{2}{5}} \tag{9}$$

The flow rate of the expanded jet can be obtained by combining equation 4 with equation 9

$$Q_{Expanded} = 0.28 L_{Tank} V_{Jet} \sqrt{b_0} \left[\frac{\left(2.41\Pi_{Jet} V_{Jet} \sqrt{b_0}\right)^3}{0.116\varepsilon_{MinBreakup}}\right]^{\frac{1}{5}} \tag{10}$$

$$\frac{Q_{Expanded}}{Q_0} = 0.28 \left[\frac{\left(2.41\Pi_{Jet} V_{Jet}\right)^3}{0.116 b_0 \varepsilon_{MinBreakup}}\right]^{\frac{1}{5}} \tag{11}$$

The maximum energy dissipation rate of the jet can be substituted into equation 11 and the constants can be combined to obtain a simplified relationship.

$$\frac{Q_{Expanded}}{Q_0} = 0.73 \left[\frac{\varepsilon_{MaxJet}}{\varepsilon_{MinBreakup}}\right]^{\frac{1}{5}} \tag{12}$$

The ratio of maximum to minimum energy dissipation rate is expected to be between 1 and 100 and thus the expanded flow is expected to be at most 1.8. Thus the entrainment of floc blanket fluid into the jet could be a significant contribution to production of small flocs. If the ratio of maximum to minimum energy dissipation rate is order 10, then the entrainment of floc blanket fluid into the jet will be insignificant and the vast majority of flocs that are broken will be flocs that had previously settled and were then resuspended by the jet.

Optimizing the floc blanket and floc weir is an important part of reducing how much water is wasted to remove the excess sludge. When optimized, it will reduce the amount of water wasted by further concentrating the flocs in the floc hopper. We will explore what floc hopper depth and surface area is needed to achieve the best floc extraction. The ideal depth will be one with the greatest sludge concentration leaving the tank without causing buildup that is difficult to remove. We would like to know both the impact of sludge depth on sludge concentration and the relationship between floc hopper plan view area on the resulting sludge concentration.

Another problem currently encountered in AguaClara plants is that there is no easy way to monitor the floc blanket. It would be easier for the operators if there was a way to see into the tank, allowing them to see floc blanket formation. They would also like to be able to monitor the depth of sludge in the floc hopper so it can be removed as needed while minimizing the wasting of water. Since the walls are made of concrete, we need to find a way for the operators to see and understand what is going on in the tank. To address the problem of floc blanket monitoring without visual aid, we wish to find the relationship between influent turbidity and time until floc blanket formation.

We already know that the floc blanket will take a longer time to form at a low turbidities because less mass is being added per unit time. Before the floc blanket is formed, smaller flocs may be able to escape into the tube settlers and out into the effluent. With knowledge of the relationship between influent turbidity and time until floc blanket formation, we will be better equipped to prevent such failures.

The floc blanket formation can be described using the principles of mass conservation, which we employed in determining how long it will take for a floc blanket to form at various turbidity levels. Mass flow into the sedimentation tank minus the mass flow out of the sedimentation tank is equal to the mass accumulation within the tank. Mass flow is calculated as Q (reactor flow rate, mL/min) multiplied by the concentration of the flocs. The amount of water entering the sedimentation tank is equal to the amount leaving, so a single Q was used. To observe a range of raw water conditions similar to those seen in Honduras, the concentrations entering the tank will be 10, 100, and 500 NTU. The concentration leaving the tank is set to 1 NTU, the target turbidity in real AguaClara plants. The mass accumulation rate within the sedimentation tank was calculated by multiplying tank volume by floc blanket concentration and divided by time to floc blanket formation. As we have not yet calculated floc blanket concentration for our experiments, we are using 2.5 g/L, the average concentration at upflow velocities of 1.2 mm/s, as reported by Hurst, 2010. The equations discussed above were re-arranged to solve for t, the time to floc blanket formation (3).

Time to Floc Blanket Formation

$$NTU_{convert} := 1\frac{mg}{L} \qquad H_{blanket} := 85cm \qquad A_{reactor} = 5.08 \times 10^{-3}\, m^2$$

$$C_{in} := 100 \cdot NTU_{convert} = 1 \times 10^{-4} \cdot \frac{gm}{mL} \qquad A_{triangle} := 0.5 \cdot 31.50cm \cdot 39.25cm = 618.188 \cdot cm^2$$

$$C_{out} := 1 \cdot NTU_{convert} = 1 \times 10^{-6} \cdot \frac{gm}{mL} \qquad V_{blanket} := A_{reactor} \cdot H_{blanket} - A_{triangle} \cdot w_{reactor} = 3.533\, L$$

$$C_{SedTank} := 0.0025\frac{gm}{mL}$$

$$t := \frac{V_{blanket} \cdot C_{SedTank}}{Q_{reactor} \cdot (C_{in} - C_{out})} = 4.065 \cdot hr$$

Figure 3: Time Until Floc Blanket Formation

Part III
Methods

1 General Set-Up

The first step of setting up the lab space was to consolidate the apparatus to make room for the new teams. We also expanded the flocculator to increase the residence time since the previous length used did not have a large enough residence time. The newly-designed flocculator is comprised of 122 meters of clear flexible PVC 0.95 cm ID tubing and 4 cardboard tubes of 4.25" OD. The plastic tubing was wrapped in a figure-eight pattern around two pairs of cardboard tubing and set vertically. Half of the tubing (61 meters) was wrapped around each pair of cardboard tubing for a coiled height of 105 cm up each pair of cardboard tubing. Therefore, the water must pass through two sets of figure-eight patterns before entering the sedimentation tank. The cardboard tubing is supported vertically by metal frames to facilitate removing air from the tubing. As previously mentioned, this new pattern will increase residence time in the flocculator and the number of collisions between particles. The previous residence time was only around 4 minutes and we increased it to around 24 minutes, as this is the residence time in full-scale AguaClara plants. See the experimental set-up below: (4)

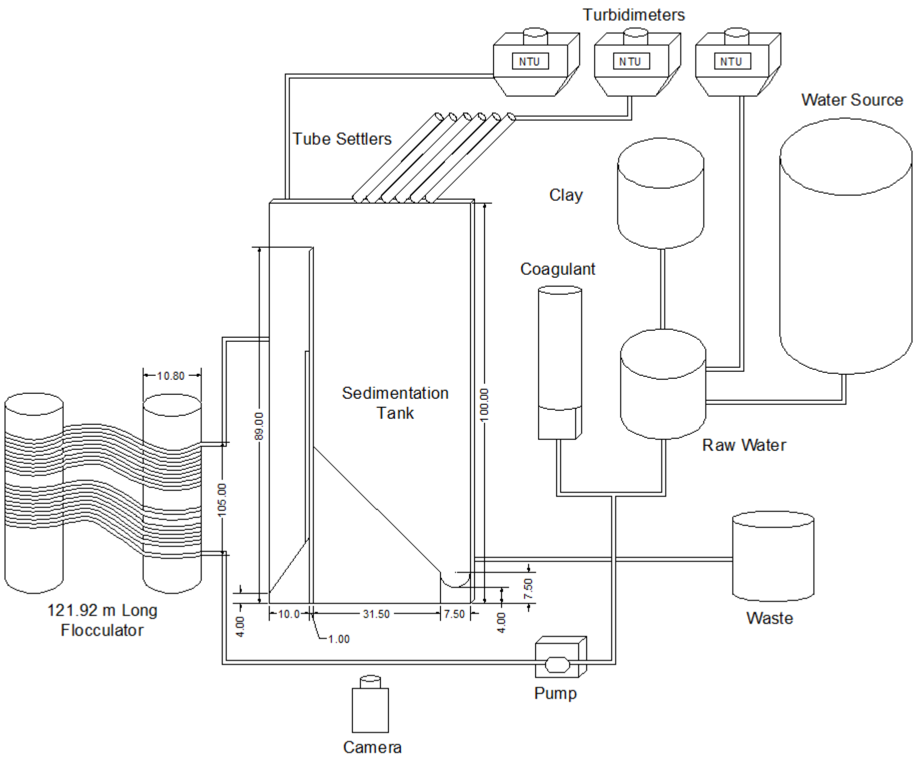


Figure 4: Experimental Set-Up

Additionally, we altered the tank geometry to make it easier to conduct our planned experiments.

Since we want to be able to vary the depths of the floc hopper, changing the geometry was important. In order to measure the depth of the hopper, we will use a new software developed by Monroe called Camera Configure in which the height of the solids/water interface is detected and returned to Process Controller. Using this software, we will be able to set the height at which the solids will be wasted from the tank. The new inserts are made out of PVC and are easily removed with a metal rod that hooks into the sides of the pieces to pull them out of the tank. The 2.5 cm strips on the side will allow for changing the size of the floc hopper to test the effect of different plan view areas. After trying to run our first experiment, we noticed some leaking of flocs from the upflow area into the hopper in the small space between the weir and the inside of the glass. To prevent this, a rubber tube that fits snugly to the glass was placed next to the weir. The following figure shows the new bottom geometry (5).

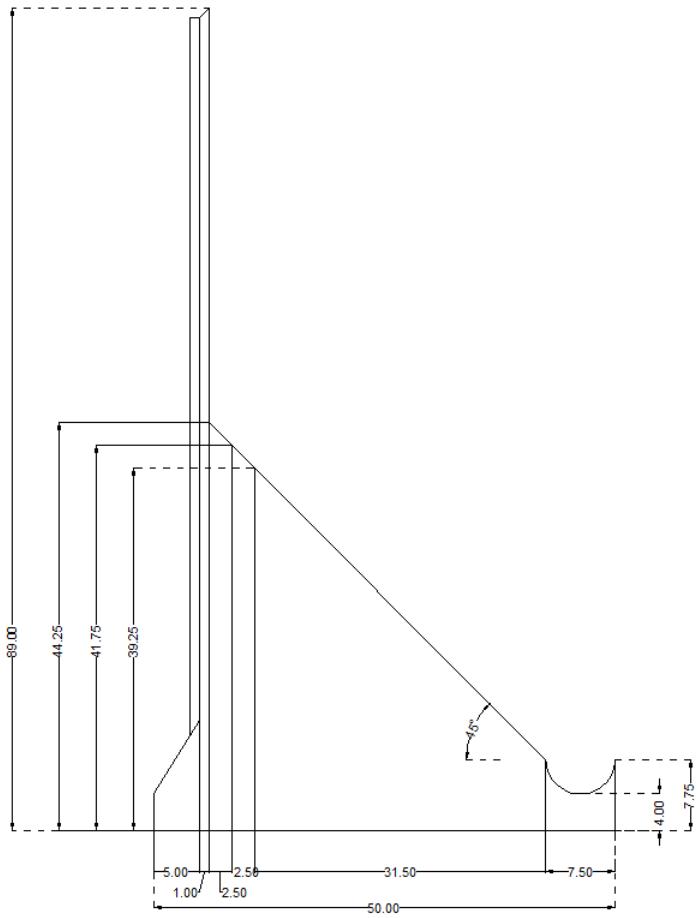


Figure 5: Sedimentation Tank Bottom Geometry

However, we are currently using the following geometry for all of our experiments (6):

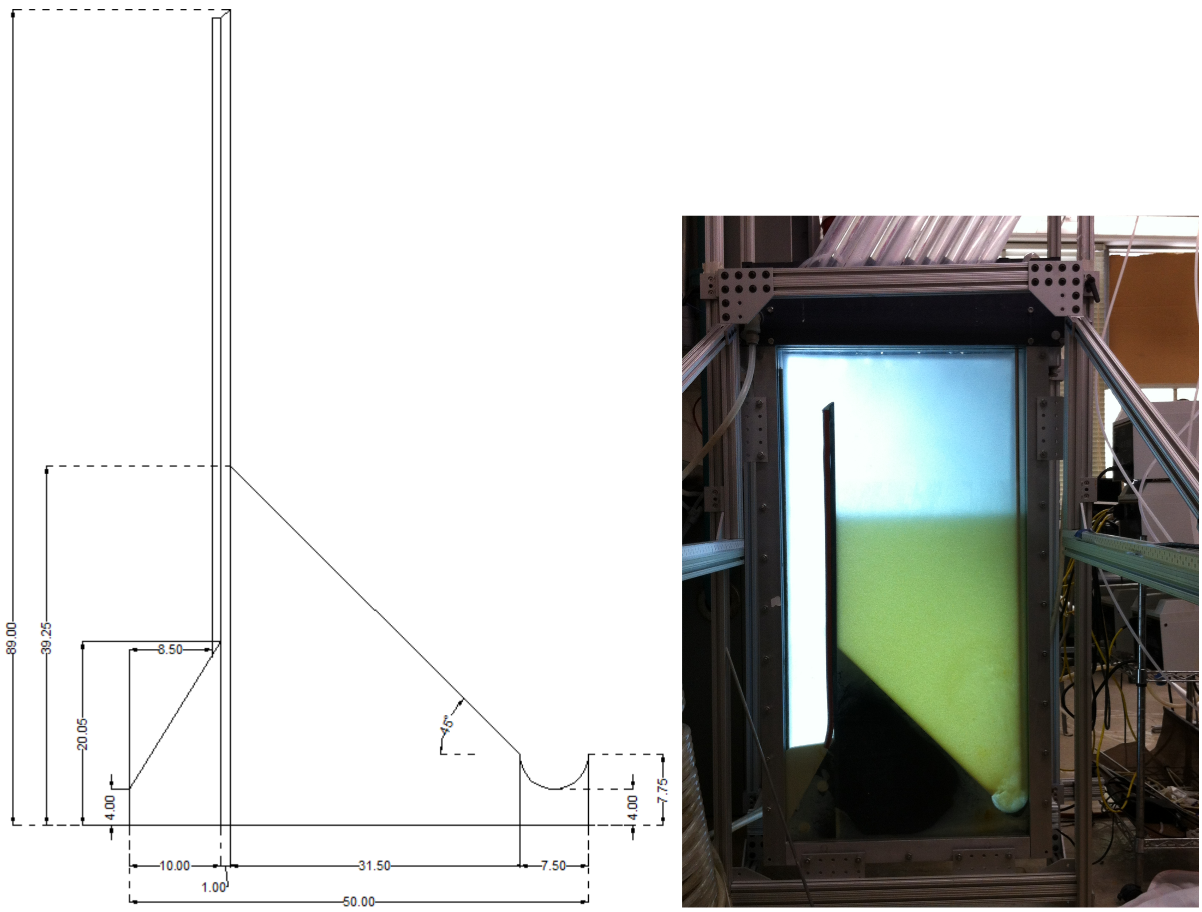


Figure 6: Sedimentation Tank Bottom Geometry

2 Experiment Plan

All of our experiments will be conducted with the layout shown above. We will have the 18% sedimentation tank plan view area floc hopper for every experiment and will be operating at an upflow velocity of 1.2 mm/sec. The following is a table showing the experiments we plan to conduct and the variables that will change.

Set	Description	Coagulant dose (mg/L)	Jet diameter (mm)	Floc hopper depth (m)	Turbidity (NTU)
1	coagulant dose	5-15 in steps of 5	9.5	0.45	100
2	nozzle size	coagulant dose that was effective	9.5, 7.9, 6.3, 4.6	0.45	100
3	floc hopper depth	coagulant dose that was effective	4.6	0.45 and 0.95	100
4	time until formation	coagulant dose (per mg/L of clay) that was effective	4.6	optimal depth	100, 800

3 Parameters

1. Conversion Factor for Tube Settlers (mL/min to RPM)

   (a) Process controller recognizes certain tubing sizes, but the tubing size used for the tube settlers is smaller those recognizable by process controller. This requires us to find another way to convert from pump speed to flow rate. The "conversion factor" was determined experimentally so that we could convert pump speed (rpm) to flow rate (mL/min). In order to do this, the experimental set-up was turned on and set to the "floc blanket formation" state, but the tube settlers' outlet tube was disconnected from the turbidimeter and fed into a graduated cylinder. After allowing the water to escape the tube settlers for one minute, 180 mL had been collected. Dividing this by the pump speed (100 rpm) gave the flow rate. Dividing again by the number of tube settlers gave the flow rate per tube settler.

Conversion Factor Calculations

$V_{measured} := 180mL \qquad Time := 1min$

$n_{settlers} := 5 \qquad RPM := 100rpm$

$$conversion := \frac{\left(\dfrac{\dfrac{V_{measured}}{Time}}{RPM}\right)}{n_{settlers}} = 0.36\,\frac{\dfrac{mL}{min}}{rpm}$$

Figure 7: Conversion from mL/min to RPM

2. Flocculator Residence Time

   (a) See the calculation below (8):

Flocculator Residence Time

$$L_{floc} := 400ft$$

$$Q_{reactor} = 365.76 \frac{mL}{min}$$

$$D_{innerfloc} := \frac{3}{8} in$$

$$Area_{floc} := \pi \cdot \left(\frac{D_{innerfloc}}{2}\right)^2 = 7.126 \times 10^{-5} m^2$$

$$V_{floc} := \frac{Q_{reactor}}{Area_{floc}} = 0.086 \frac{m}{s}$$

$$Time_{residencefloc} := \frac{L_{floc}}{V_{floc}} = 23.752 \, min$$

Figure 8: Flocculator Residence Time Calculations

3. Velocity Gradient

   (a) The velocity gradient (G) in the flocculator was calculated as follows (9). Energy dissipation rate in the lab flocculator is a function of the velocity of the fluid and the inner diameter of the tubing.

Velocity Gradient of the Flocculator, G

$$Gfloc := \sqrt{\frac{\varepsilon floc}{\nu}} = 71.522 \frac{1}{s}$$

Figure 9: Flocculator Velocity Gradient (G) Calculation

4. Plant Flow Rate (10)

   (a) One of the constraints on the plant flow rate is that we set the upflow velocity to be 1.2 mm/sec. The upflow velocity is multiplied by the upflow area of the sedimentation tank.

This area is 0.4 m x 0.5 m, which was changed from previous semesters due to the new bottom geometry of the tank

Flow Rate

$l_{reactor} := 0.4 \cdot m$

This will change based on the floc hopper width to adjust for the different upflow areas.

$w_{reactor} := 0.5 \cdot in$

$A_{reactor} := l_{reactor} \cdot w_{reactor}$

$V_{up} := 1.2 \cdot \frac{mm}{s}$

$Q_{reactor} := V_{up} \cdot A_{reactor}$

$Q_{reactor} = 6.096 \cdot \frac{mL}{s}$

Figure 10: Plant Flow Rate Calculations

5. Flow Rate and Capture Velocity in Plate Settlers

   (a) In previous years, the flow over the wasting weir was kept constant and used to determine flow through the tube settlers, which then was used to calculate the tube settler capture velocity. This year, we are setting the capture velocity to be a constant 0.12 mm/s, in order to mimic an AguaClara plant. With this capture velocity, we can calculate the tube settler flow rate. This new flow was then divided by the "conversion factor" to find the necessary RPM. The pump controlling the plate settlers should be set to 157.5 rpm given 5 tube settlers each having a flow of 56.7 mL/min and a capture velocity of 0.12 mm/s.

   (b) We also wanted to be sure that the tube settler flow rate is not greater than the flow through the plant; to do this, we multiplied tube settler flow rate by the number of tube settlers. Since the total flow calculated using 10 tube settlers is larger than the plant flow, we reduced the number tube settlers to 5. This gave us a total tube settler flow rate of 283.5 mL/min, which is a good number, since the flow is less than the plant flow rate but still uses the majority of the flow, so only 82 mL/min flow over the wasting weir. To reduce the number of tube settlers, we closed flow to the two tube settlers on either end and three others that were not previously working as efficiently. See equations below: (11).

Alternative Plate Settler Calculations

$$vcap := \frac{d_{tube} \cdot Vup}{L_{tube} \cdot \sin(\alpha)\cos(\alpha) + d_{tube}} \qquad Vup := \frac{Q_{tube}}{\left[\frac{\pi (d_{tube})^2}{4}\right]}$$

we can then insert the Vup equation into the Qtube equation and rearrange

$$L_{tube} = 85.295 \cdot cm \quad \alpha = 60 \cdot deg \quad d_{tube} = 1 \cdot in$$

$$vcap := 0.12 \frac{mm}{sec}$$

$$QTube := \frac{L_{tube} \cdot \sin(\alpha)\cos(\alpha) + d_{tube}}{4} \cdot \left[\pi (d_{tube}) \cdot vcap\right] = 56.698 \cdot \frac{mL}{min}$$

$$conversion := 0.360 \frac{\frac{mL}{min}}{rpm}$$ calculation for this conversion factor is included below

$$RPM := \frac{QTube}{conversion} = 157.494 \cdot rpm$$

$$n_{tube} := 10$$

$$Qplatesettlers := QTube \cdot 10 = 566.977 \cdot \frac{mL}{min} \qquad Q_{reactor} = 365.76 \cdot \frac{mL}{min}$$

$$Q_{suggest} := 5 \cdot QTube = 283.488 \cdot \frac{mL}{min} \qquad qweir := Q_{reactor} - Q_{suggest} = 82.272 \cdot \frac{mL}{min}$$

Figure 11: Plate Settler RPM Calculations

6. Area Measurements
   (a) Upflow Area
      i. 39 cm x 1.27 cm = 49.5 cm^2
   (b) Floc Hopper Area
      i. 8.5 cm x 1.27 cm = 10.8 cm^2
      ii. The width of 7.5 cm is calculated by taking the entire width of the tank (50 cm) and subtracting the upflow width (39 cm), weir width (1 cm), and the width of the rubber tubing (1.5 cm).
   (c) Ratio of Floc Hopper Area to Upflow Area: 10.8 cm^2 / 49.5 cm^2 = .18

7. Coagulant Flow Rate and Stock Concentration
   (a) The coagulant flow rate is calculated using the stock concentration and the desired coagulant dose. For coagulant doses of 10 and 15 mg/L, we used a stock concentration of 666 mg/L, and for 5 mg/L we used a stock concentration of 500 mg/L. We had to decrease the stock concentration for the lower coagulant dose because the pump cannot operate below 1.6 rpm. Thus, we used a safety factor of about 2.8 and kept our flow rate above 4.5 rpm. See the sample calculation and table below (12,1).

Table 1: Coagulant Flow Rates

Stock Concentration (mg/L)	Desired Coagulant Dose (mg/L)	Coagulant Flow Rate (mL/min)	Coagulant Pump RPM
666	15	8.23	10.3
666	10	5.49	6.86
500	5	3.66	4.57

PACl Stock Flow Rate

$V_{stock2} := 3L$

$C_{Reactor2} := 15 \cdot \frac{mg}{L}$

$m_{alum2} := 2gm$

$C_{alum2} := \frac{m_{alum2}}{V_{stock2}} = 666.667 \frac{mg}{L}$

$Q_{alum2} := Q_{reactor} \cdot \frac{C_{Reactor2}}{C_{alum2}} = 8.23 \cdot \frac{mL}{min}$

Figure 12: Coagulant Flow Rate Calculations

Part IV
Analysis

1 Coagulant Dosage

- Three experiments were performed to compare the effect of different PACl coagulant concentrations: 15, 10 and 5 mg/L. Prior testing determined the 5 best tube settlers to be utilized based on the performance of the pump. Influent turbidity, energy dissipation rate and floc hopper height remained constant as shown in the Parameters section. The main criteria used to qualify the results is the effluent turbidity. To determine the average effluent turbidity of each dosage, the effluent data recorded over the duration of the floc blanket steady state was averaged. This steady state was determined by analyzing the photographs taken through the Camera Configure program. We considered steady state to be when the blanket reached and maintained its maximum height. The average effluent turbidities for each coagulant concentration are displayed in the table below (2). Also, see the graphs of effluent turbidity vs. time for each of the coagulant doses (13,14,15).
- We observed floc blanket failure at a coagulant concentration of 5 mg/L and a jet reverser

inner diameter of 0.95 cm. The energy dissipation of the jet reverser was not high enough to keep the particles suspended after the floc blanket reached a height of about 65 cm because the particles became more concentrated and consequently heavier, settling on the bottom of the floc hopper. The velocity of the flow out of the jet reverser could not create enough momentum to elevate the particles. As floc concentration increased at this height, particles began sliding down the inclined side of the sedimentation tank, but were not able to be re-suspended by the jet reverser. Within about five minutes, the semi-circle at the bottom of the tank was filled with flocs and the flow from the jet reverser was forced to move straight up the side of the tank. Since the jet reverser was no longer re-suspending flocs, the blanket quickly collapsed.

Table 2: Coagulant Dosage Results

Coagulant Dosage (mg/L)	Effluent Turbidity (NTU)	Video Hyperlinks
15	0.73	15 mg/L Coagulant Dose
10	0.675	10 mg/L Coagulant Dose
5	0.675	5 mg/L Coagulant Dose

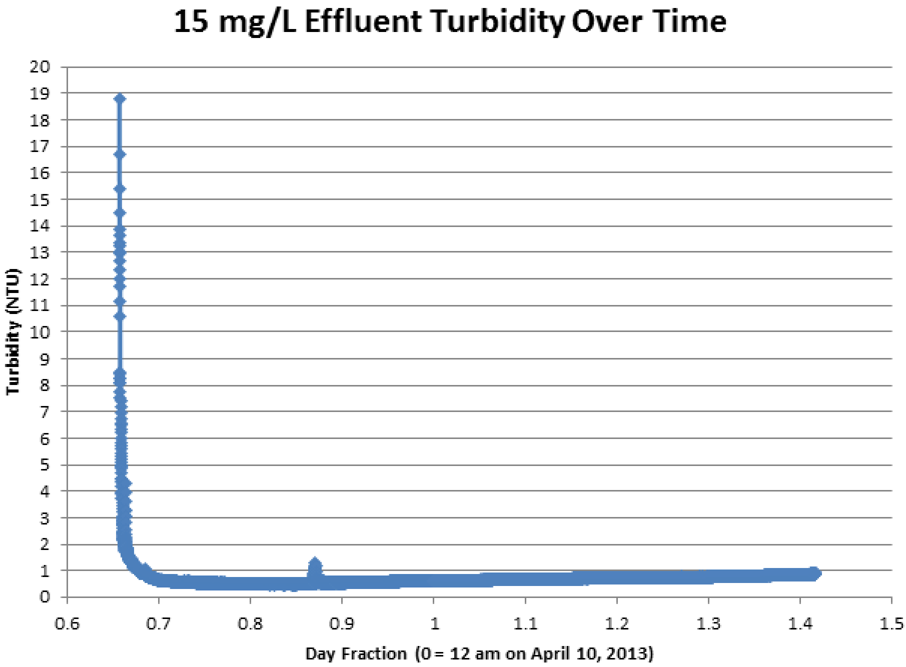


Figure 13: Graph of Effluent Turbidity vs. Time: 15 mg/L

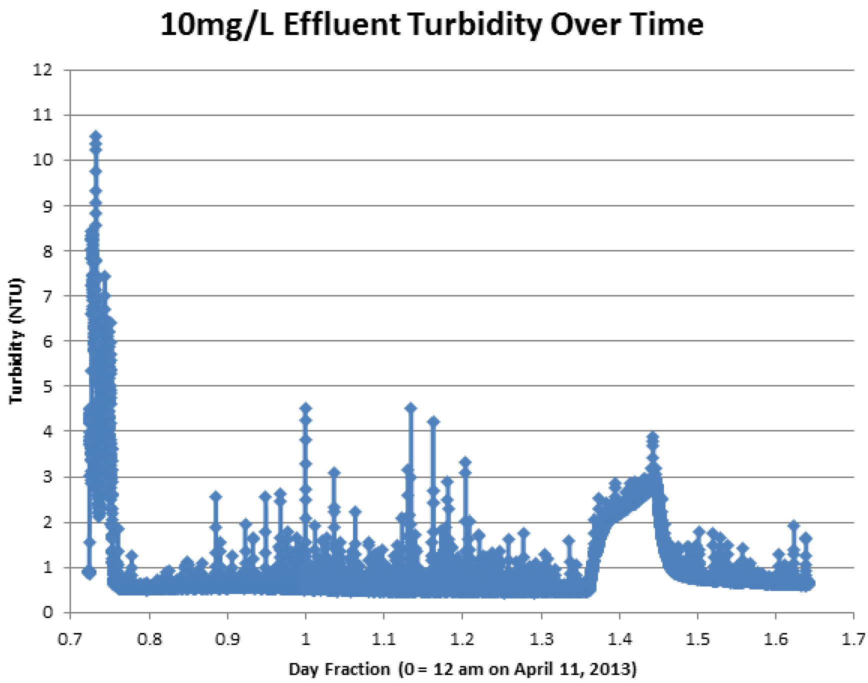


Figure 14: Graph of Effluent Turbidity vs. Time: 10 mg/L

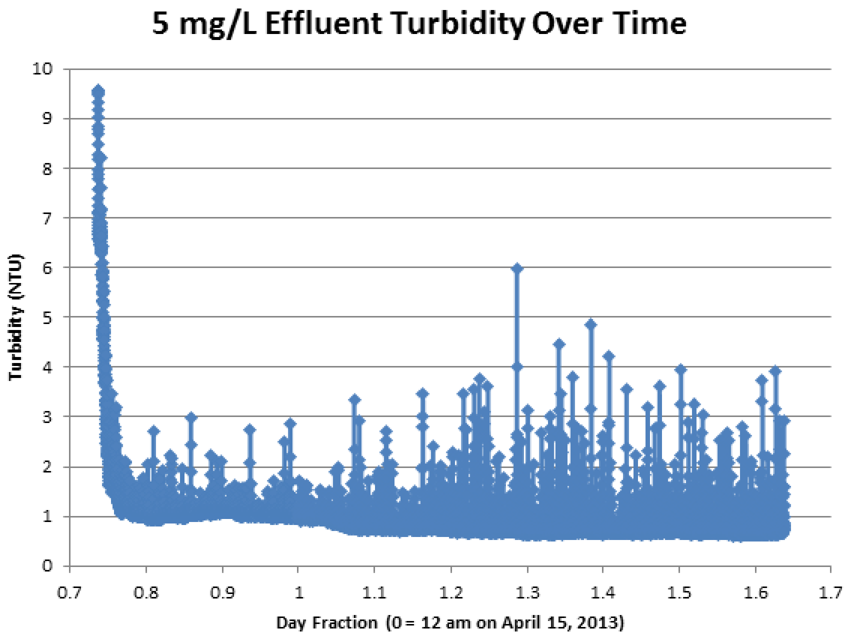


Figure 15: Graph of Effluent Turbidity vs. Time: 5 mg/L

2 Jet Reverser Diameter

- Originally, we wanted to test different nozzle sizes for the jet to observe the effects of varying energy dissipations on the floc blanket performance. However, we determined that it would be too expensive to buy different sized nozzles for the jet. Instead, we ordered pipes ranging between 0.46 cm and 0.95 cm ID in order to explore a significant range of energy dissipation (1-100 mW/kg). The energy dissipation rates were calculated using the following equation: $\varepsilon = \frac{\left(\prod_{jet} V\right)^3}{D} = \frac{\left(4\prod_{jet} Q\right)^3}{\pi^3 D^7}$. See the table below for a sample calculation of the energy dissipation (16).

Energy dissipation calculations

$$PiJet := 0.225$$

$$Q_{reactor} = 6.096 \times 10^{-6} \frac{m^3}{s}$$

$$Ddiffuser = 0.952\,cm \qquad Adiffuser := \frac{\pi \cdot Ddiffuser^2}{4} = 0.713\,cm^2$$

$$Vdiffuser := \frac{Q_{reactor}}{Adiffuser} = 0.086\,\frac{m}{s}$$

$$ED := \frac{(PiJet \cdot Vdiffuser)^3}{Ddiffuser} = 0.749 \cdot \frac{mW}{kg}$$

Figure 16: Energy Dissipation Calculations for 0.95 cm ID pipe

- An experiment was conducted to test the influence of energy dissipation on the performance of the floc blanket by changing the diameter of the inflow jet pipe. The coagulant dose was set to 5 mg/L, as this was the most effective PACl dose found in the Coagulant Dosage experiment. The 5 mg/L dose yielded the lowest effluent turbidity while also using the least amount of PACl as shown in table (2). The major criteria to analyze these experiments is also the effluent turbidity using the chosen coagulant concentration and maintaining all the other parameters constant. The first experiment was started during the state of failure of the floc blanket as the inner diameter of the jet pipe was switched from 0.95 cm to 0.46 cm. After manually stirring up the flocs to facilitate re-suspension, the floc blanket that had settled in the upflow area began to re-form.

- When switching between jet reverser diameters, extra manual stirring was needed to start the re-suspension of the floc blanket. The 0.79 cm diameter jet had the most difficulty re-suspending the floc blanket (after switching from 0.63 cm). After completing the experiments with manual resuspension of the floc blanket, each jet diameter was used to create a floc blanket from scratch, and the effluent turbidity (NTU) for each diameter was recorded.The method to calculate the effluent turbidity was the same as was used in the coagulant dosage experiment. (The turbidity values at floc blanket steady-state were averaged.) See the table below (3):

Table 3: Jet Reverser Diameters and Energy Dissipations

Inner Diameter (cm)	Energy Dissipation Rate (mW/kg)	Effluent NTU with Manual Resuspension	Effluent NTU From Scratch	Video Hyperlink: Resuspension	Video Hyperlink: From Scratch
0.95	0.76	n/a	0.68	n/a	5 mg/L Coagulant Dose
0.79	2.8	2.36	2.85	0.79 Diameter Energy Dissipation Rate Resuspended	0.79 Diameter Energy Dissipation Rate
0.63	13	0.83	2.15	0.63 Diameter Energy Dissipation Rate Resuspended	0.63 Diameter Energy Dissipation Rate
0.46	130	0.66	0.75	0.46 Diameter Energy Dissipation Rate Resuspended	0.46 Diameter Energy Dissipation Rate

- See graphs below depicting the effluent turbidity over time for the varying energy dissipation rates (17, 18, 19, 20).

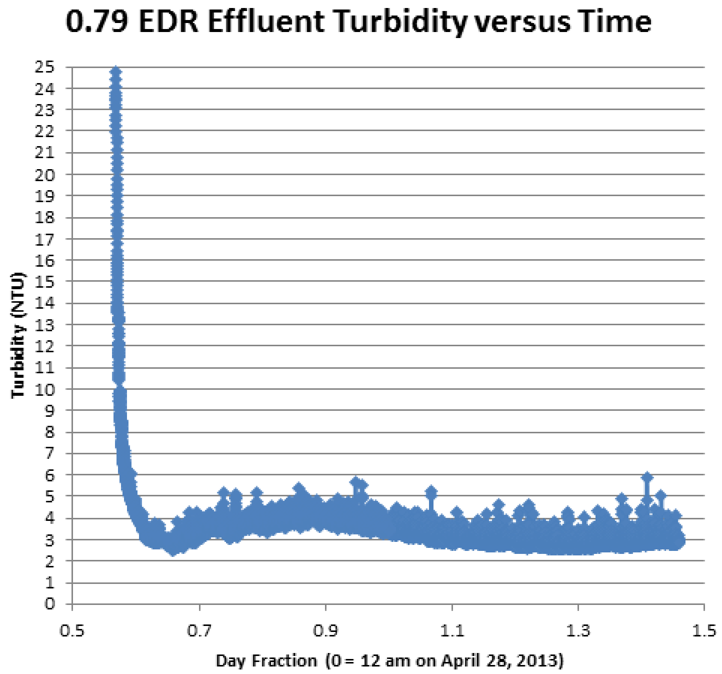


Figure 17: Graph showing effluent turbidity vs. time: 2.8 mW/kg

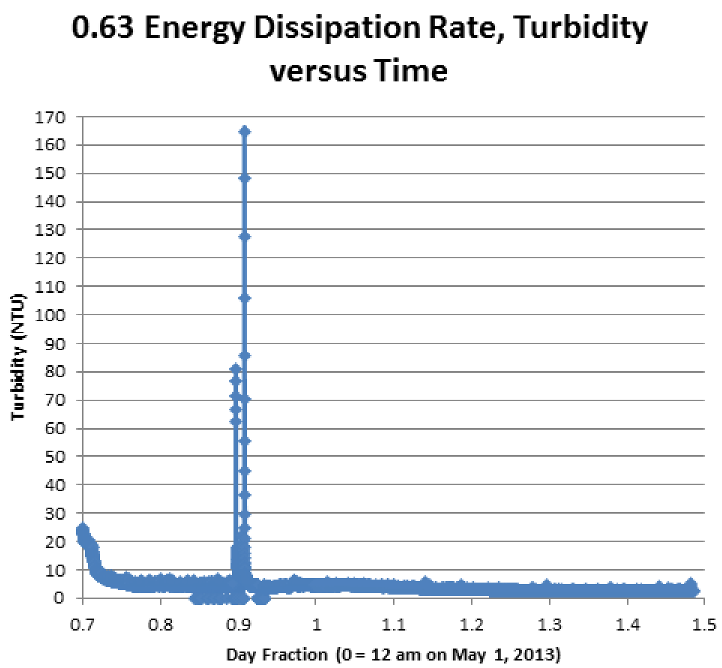


Figure 18: Graph showing effluent turbidity vs. time: 13 mW/kg

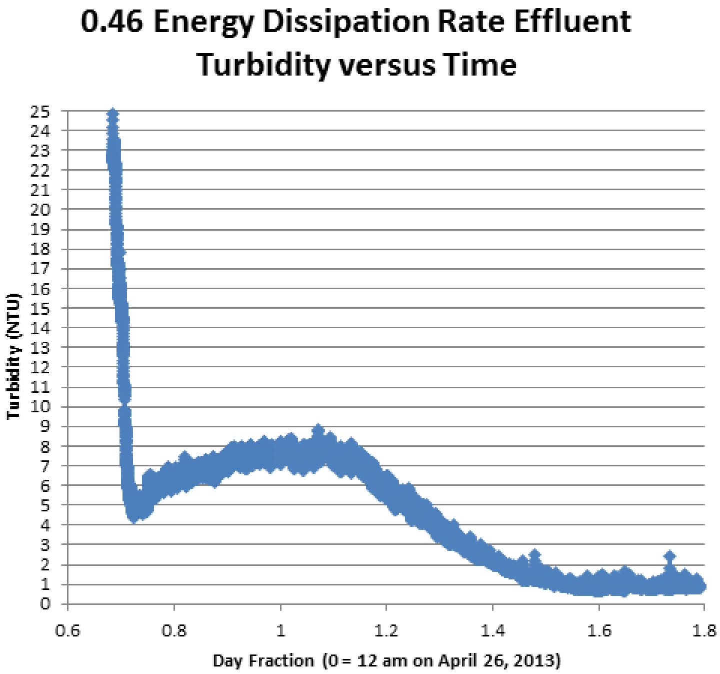


Figure 19: Graph showing effluent turbidity vs. time: 130 mW/kg

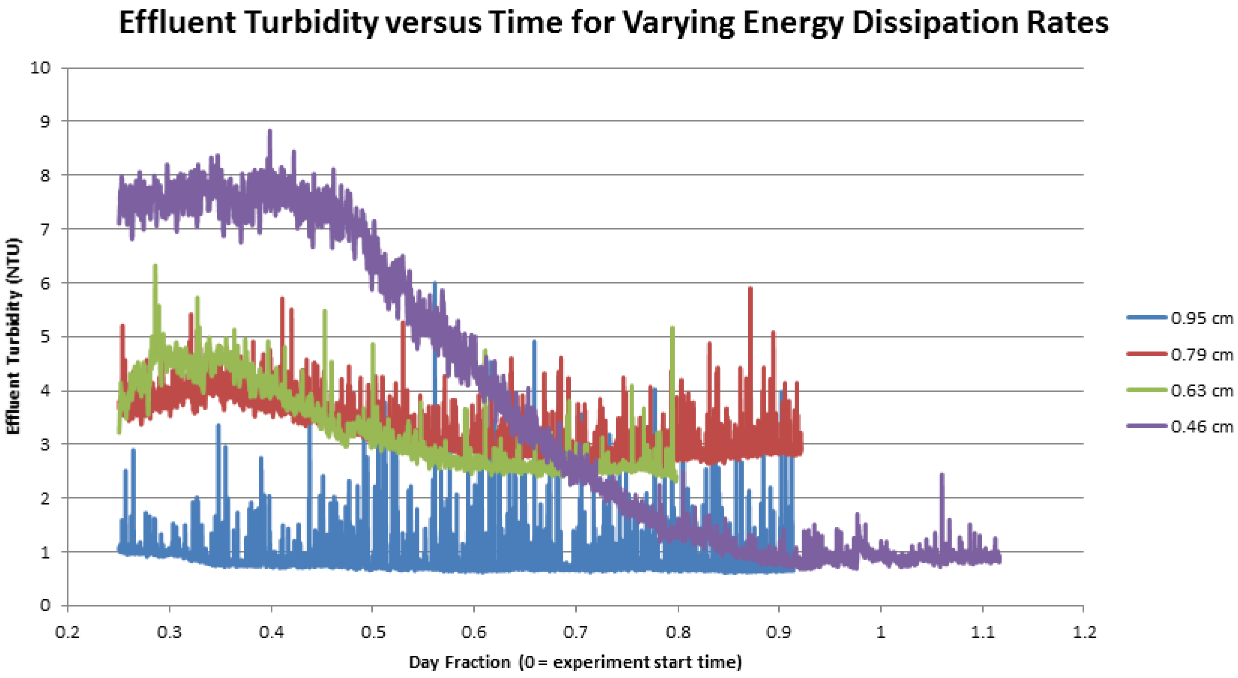


Figure 20: Effluent Turbidity vs. Time for Varying Energy Dissipations

3 Dye Test

To better visualize the flow paths within a steady-state floc blanket, a pulse of red dye was sent through the jet reverser and into the blanket created at two different influent turbidities and coagulant dosages. The first dye test was on a dilute blanket created at an influent turbidity of 800 NTU and coagulant dose of 30 mg/L, while the second test was run with a denser blanket created with an influent NTU of 100 and a coagulant dose of 5 mg/L. The 100 NTU blanket is more dense because we had optimized the coagulant dose for 100 NTU in our Coagulant Dosage experiment. However, for the 800 NTU test, we estimated a suitable coagulant dosage (30 mg/L). The red dye was at a concentration of 49 g/L and a 10 second pulse entered the tank after the flocculator but before the jet reverser. The mass of dye injected was 0.15 grams at a flow rate of 18.3 mL/min. This was controlled by a "dummy pump" running at 23% and controlled manually. The dye travelled through small flexible tubing, starting from the stock bottle, running through the pump to a T-shaped connection, where it joined the flow from the flocculator and entered the jet reverser. When the pulse of dye exited the jet reverser, it traveled in a semi-circular motion, following the jet reverser curvature until it met the stream of particles moving down the sloped bottom of the sedimentation tank; at this point, the two flows intersected and moved towards the right-hand wall of the tank at about a 45° angle. The dye then traveled upwards along the right-hand wall of the tank until it reached a height of approximately 20 cm, where the tank geometry becomes rectangular. At this point, the dye spread out and mixed with the water in the triangular part of the tank and then moving up into the rest of the tank. As the dye moved to the top of the sedimentation tank, its behavior began to model plug flow.

The time for the dye to reach the top of the floc weir (the hydraulic residence time) was measured and compared to the time it took for the dye to completely leave the the sedimentation tank for both the dilute and dense floc blankets. The values are as follows (4):

Table 4: Dye Hydraulic Residence Times

	Influent NTU	Coagulant Dose (mg/L)	Hydraulic Residence Time (minutes)	Time to Complete Dye Removal (minutes)	Video Hyperlink of Full Dye Test	Video Hyperlink of First 5 Minutes
Dilute Floc Blanket	800	30	3.55	28.98	Red Dye Flow Path Experiment at 800 NTU	First 5 Minutes of 800 NTU Dye Test
Dense Floc Blanket	100	5	6.18	30.17	Dye Flow Test at 100 NTU and 0.63 Diameter EDR	Dye Flow Test at 100 NTU and 0.63 Diameter EDR First 5 Minutes

4 Varying Influent Turbidity

The bulk of the experiments were conducted at an influent of 100 NTU. However, to simulate the high-intensity rainstorms with extremely turbid waters that are sometimes seen in Honduras, an influent turbidity of 800 NTU was tested. For this experiment, the coagulant was dosed at 30 mg/L to deal with the higher influent turbidity. We also ran an experiment at 10 NTU with the same coagulant to NTU ratio as the 100 NTU experiment, however we were unable to form a floc blanket.

5 Changing Floc Hopper Depth

We collected 100 mL samples of sludge from the floc hopper at two different floc hopper depths. The first depth was set at a minimum of 45 cm and a maximum of 50 cm from the floor. The second depth was set at a minimum of 95 and a maximum of 100. See the images below showing the floc hopper at depths of 45-50 cm and 95-100 cm (21). We were interested to see if the two different samples would contain a different amount of sludge. First, we let them settle in their containers to see if there was a visual difference. After 48 hours of settling, both samples were dried in an oven and massed to determine the mass percentage of sludge collected.

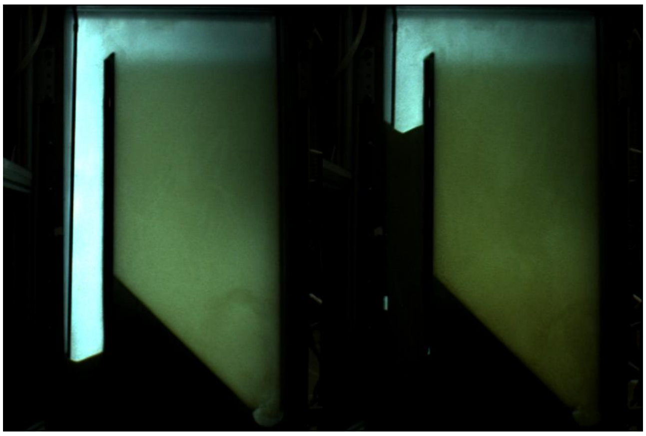


Figure 21: Floc hopper depths: 45-50 cm (a) and 95-100 cm (b)

Part V
Conclusions

Varying Coagulant Dose

The results of the coagulant dosage experiments showed that of the three PACl doses tested (5, 10, and 15 mg/L), the 5 and 10 mg/L doses resulted in the lowest effluent turbidities, which, at steady state, averaged 0.675 NTU for both experiments. However, when testing the 5 mg/L dosage, the floc blanket collapsed after 24.8 hours because the jet reverser (0.76 mW/kg) could not re-suspend the highly concentrated flocs. The jet could not re-suspend the flocs at this energy dissipation because the momentum of the flocs flowing down the incline exceeded that of the jet reverser. See a video of this failure and resuspension here: Floc Blanket Collapse and Resuspension. Up until it failed, the floc blanket performed just as well as the fully-formed floc blanket in the 10 mg/L test. Because the 10 and 5 mg/L tests resulted in the same effluent turbidities, 5 mg/L was chosen as the optimal coagulant dose to reduce the amount of PACl required and save money.

Varying Energy Dissipation Rate

When using the optimal PACl dosage of 5 mg/L, effluent turbidity tended to increase with decreasing energy dissipation rate. The exception is the lowest energy dissipation rate (prior to floc blanket collapse), 0.76 mW/kg, for which the jet reverser had an inner diameter of 0.95 cm and the average effluent turbidity was 0.68 NTU. The optimal energy dissipation rate was determined to be 130 mW/kg, which was obtained using a jet reverser with an inner diameter of 0.46 cm. The floc blanket formed under these conditions had an average effluent turbidity of 0.66 NTU for resuspension, and 0.75 NTU from scratch. The flocs observed were small and densely clustered together, but did not get sucked out of the tube settlers. This finding is significant for application in full-scale sedimentation tanks, because a better floc blanket can be made using a smaller jet reverser, which reduces material costs while increasing performance. This finding also dispelled the concern that the energy dissipation rate in the transition from the flocculator to the sedimentation tank needs to be the same as in the flocculator to avoid floc breakup. Further study is required to understand whether a high energy dissipation rate at the inlet to the sedimentation tank has other unintended consequences such as causing poor performance when using a low coagulant dose that produces small flocs.

Varying Influent Turbidity - Time to Formation

For the 800 NTU experiment, a floc blanket formed in two hours, which is about 11 times faster than the 100 NTU experiment, which took almost 22 hours. The floc blanket appeared to have a lower concentration than previous floc blankets, which may be due to using too much coagulant. However, the amount of coagulant per mass of clay was lower for the 800 NTU test (3.75 mg/L / 100 NTU) and thus was lower than the dose of 5 mg/L used for all of the 100 NTU tests. The average effluent turbidity was 1.69 NTU at steady-state; however, as time went on, the effluent turbidity began to increase. The floc blanket lost integrity (after 16 hours), as flocs were sucked into the tube settlers. Eventually, the concentration of unsettled flocs within the floc weir was the same as the concentration within the blanket. This may have occurred because as the height of the sludge grew, the flocs did not have enough room to reach settling velocity and become more concentrated. Due to the higher NTU the flocs were flowing over the weir faster than they could settle, causing failure. This failure mode is actually a failure of the floc hopper not the floc blanket. See the video of the 800 NTU experiment here: 800 NTU Floc Blanket Formation and a graph of effluent turbidity over time (22). A video was not created for the 10 NTU experiment because a floc blanket was unable to form.

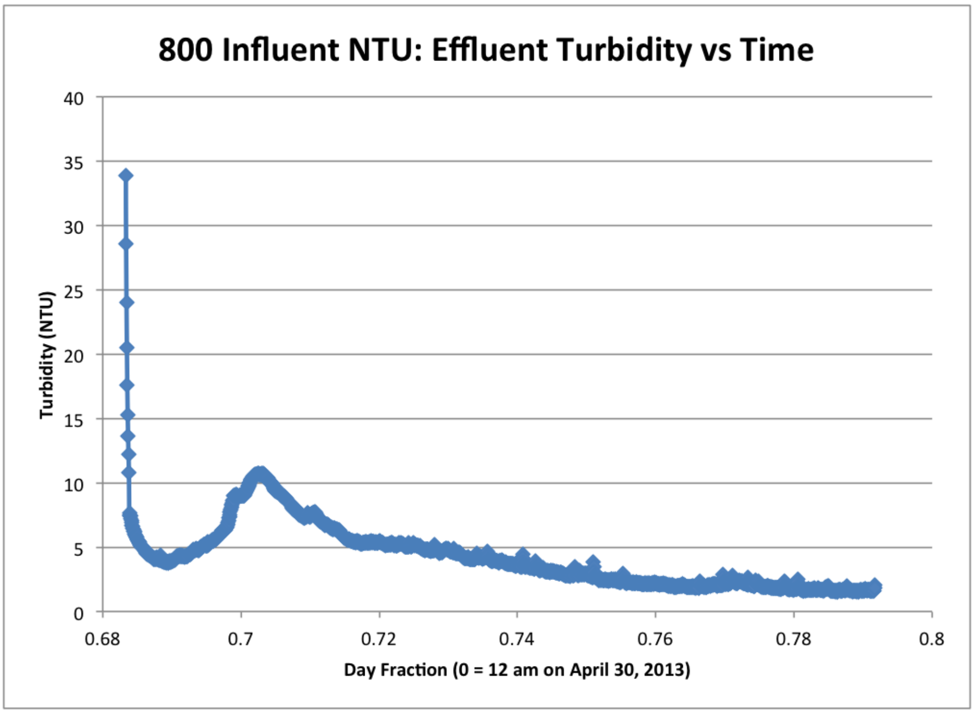


Figure 22: Graph depicting effluent turbidity over time for 800 NTU influent turbidity

PACl Discoveries

Through our experimentation, we have reaffirmed that PACl is stickier than alum. We saw this mainly in two places. First, we noticed that the flocculator needed to be cleaned more frequently, every 2-3 experiments. This is due to the fact that more particles were attaching themselves to the inside of the flocculator tubes. We also observed that particles stuck to the glass plates in the sedimentation tank. This will cause inaccuracy in concentration measurements based on image analysis and potentially effect floc blanket formation and settling in the floc hopper. Thus, we were unable to determine how the concentration of the floc blanket varied over the height. Below are images showing how the PACl stuck to the sides of the sedimentation tank and how we attempted to knock them off with a metal rod. As shown, there is a distinct line where the PACl is still sticking to the side of the tank (23).

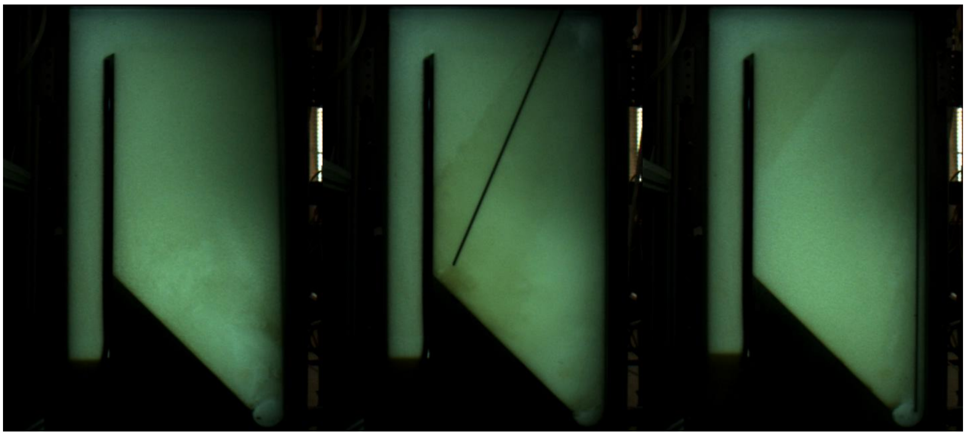


Figure 23: (a) PACl sticking to the side of the sedimentation tank; (b) Using metal rod to clean off the glass; (c) Clear line of coagulant still stuck to glass

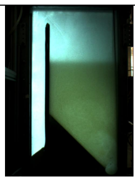
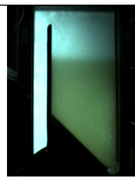
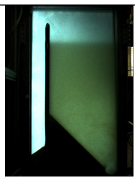
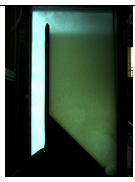
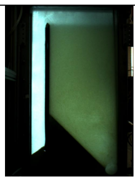
Dye Test Conclusions

The video of this test (as shown in table 4) shows that the dye mixes rapidly within about 20 cm of the inlet, behaving as a complete mix flow reactor, and transforms into plug flow as the fluid moves toward the top of the blanket.The dye test for the more dilute blanket revealed that there were no preferential flow paths all the way through the blanket, which is good because it means that flocs are interacting with each other in the floc blanket rather than escaping quickly. However, in the video for the denser floc blanket created with an influent turbidity of 100 NTU, there is evidence of a preferential flow path, at least initially. It is clear that the dye moved more quickly up the right side of the sedimentation tank, along the side of the jet, creating a diagonal interface of the dye and the unaffected floc blanket above it. Once the dye reached about halfway up the floc blanket, the diagonal interface moved uniformly at a velocity of 1.2 mm/s, and eventually became horizontal as it reached the very top of the floc blanket.

Effluent Turbidity vs. Floc Blanket Height

Previously, it was believed that floc blanket depth was correlated to effluent turbidity, because the floc blanket was believed to act like a filter, so that at higher depths, floc blanket performance would increase and effluent turbidity would decrease. Hurst hypothesized that for floc blanket heights above 55 cm, the effluent NTU is not greatly affected. We explored this hypothesis further by analyzing our data for the Energy Dissipation Experiment with jet diameters of 0.46 and 0.79 cm and an influent turbidity of 100 NTU. We chose these jet diameters to compare the floc blanket formation and effluent turbidities at both low and high energy dissipation rates. We did not use the smallest energy dissipation rate (0.76 mW/kg with the 0.95 cm jet diameter), since failure was observed using this diameter. At energy dissipation rates of 130 mW/kg and 2.8 mW/kg, we chose various heights based on the max height of the blanket (85 cm) and the height at which the blanket obtained uniform density (46.5 cm). We did not use data points below 46.5 cm in our analysis because the blanket did not form before that height. The dilute floc-water interface rose to 46.5 cm before it actually became dense enough to form a blanket. Since we are analyzing effluent turbidity vs. floc blanket height, we start our analysis at the beginning of floc blanket formation. Thus,the effluent NTU was recorded at the maximum and minimum heights as well as various heights in between at 10 cm intervals. Additional heights were analyzed at the top of the weir to see if, after the first 65 cm, there was a significant change in effluent turbidity. As shown in the table, between 80 cm and 85 cm, the effluent turbidity for the 0.46 cm jet diameter still decreases by 0.12 NTU. This suggests that floc blanket performance increases with increased height of the floc blanket. The effluent turbidity decreased with height for the 0.79 cm jet, as well. However, this decrease is less significant than that in the 0.46 cm jet, as the effluent turbidity only changed from 2.72 to 2.70 NTU between 80 and 85 cm.

Table 5: Effluent Turbidity vs. Floc Blanket Height for Energy Dissipation Rates of 130 and 2.8 mW/kg

Height (cm)	Time 0.46 cm Jet	Effluent Turbidity (NTU) 0.46 cm Jet	Image 0.46 cm Jet	Time 0.79 cm Jet	Effluent Turbidity (NTU) 0.79 cm Jet	Image 0.79 cm Jet
46.5	4:40 am	5.96		12:03 am	3.35	
55	7:28 am	3.52		1:46 am	3.11	
65	9:51 am	2.15		4:13 am	2.82	
75	12:11 pm	1.26		6:01 am	2.73	
80	1:11 pm	0.91		6:39 am	2.72	
85	1:48 pm	0.79		8:56 am	2.70	

See the following graph depicting pC* vs. height of the floc blanket for both the 0.46 cm and 0.79 cm jet diameters (24) and another showing floc blanket growth over time (25):

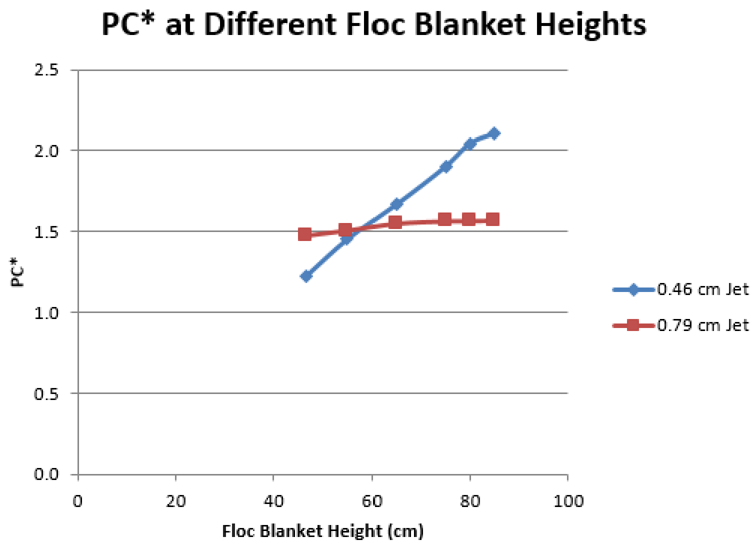


Figure 24: Graph showing pC* vs. floc blanket height: 2.8 mW/kg and 130 mW/kg

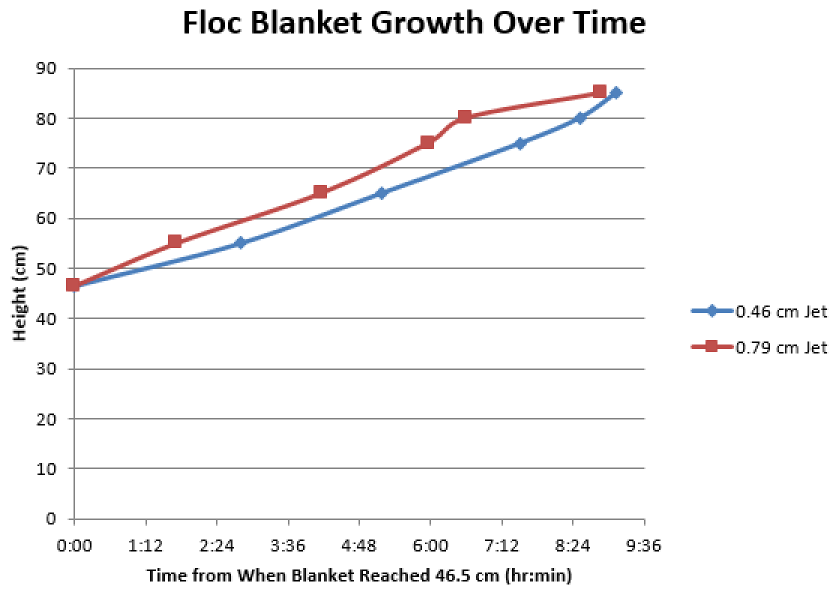


Figure 25: Graph depicting floc blanket growth over time: 2.8 mW/kg and 130 mW/kg

Running Out of Coagulant

We created a video of the floc blanket behavior when it runs out of coagulant. This was done using the data from the 100 NTU influent, 5 mg/L coagulant dose, and a 0.46 cm diameter jet experiment.

When watching the video we see an interface of denser particles move up the floc blanket; this takes approximately 8.5 minutes, which is slower than the hydraulic residence time of the dye which was 6.18 minutes. When these particles reach the top there is a large disturbance along the right hang side (where the jet reverser is located). The disturbance created a wave along the top of the floc blanket and caused the area above the weir and the floc hopper to fill with particles. Then the particles begin to spread out until there is no longer a floc blanket. The instability that caused the disturbance in the floc blanket could be due to the change in density and suspension properties of the particles. Since these particles were no longer receiving coagulant, the clay particles are not sticking to each other and would be very small. Since the water flowing in only has smaller particles it is less dense and creates a preferential flow path up the right side of the reactor causing the disturbance and mixing. See the video here: Out of Coagulant Failure.

Jet and Debris Flow Interaction

As the momentum of the jet decreases (with larger jet diameters and lower energy dissipation rates), the angle at which the jet flow comes off of the semi-circular bottom geometry decreases. See the images below for energy dissipation rates of 2.8, 13, and 130 mW/kg (26). This is the result of the interaction of the jet with the debris flow down the triangular portion of the bottom geometry. At smaller energy dissipation rates, the jet does not have enough momentum to overcome the debris flow, and thus, the debris forces the flow to leave the semi-circle at a shallower angle.

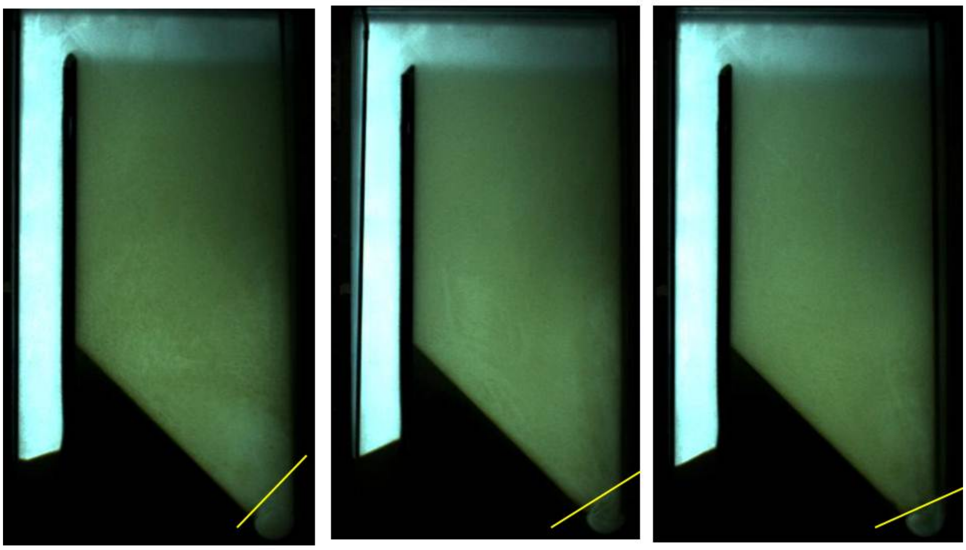


Figure 26: Figures showing jet and debris flow interaction at energy dissipation rates of (a) 130, (b) 13, and (c) 2.8 mW/kg

Sludge Consolidation

When collecting the 100 mL samples, the sludge collected at a floc hopper depth of 95-100 cm was visibly thicker, suggesting a greater sludge concentration than the 45-50 cm depth sample. After leaving the samples to settle for 48 hours, there were observed differences in the settling between the two samples. The sample collected at a floc hopper depth of 95 cm appeared to have a higher sludge content. To test if the 95-100 cm sample contained a higher sludge content, the samples were filtered and dried in an oven at 105 degrees celsius for 4 hours. The samples were then massed. The 45-50 cm sample had a mass of 6.38 grams, where as the mass of the 95-100 cm was found to be 12.36 grams. This proves that with greater floc hopper depths, sludge concentration increases, and that compressive settling occurs in the floc hopper. See the images below, showing the samples before and after settling (27).

Figure 27: Sludge Samples before (a) and after (b) settling: 45-50 cm (left flask) and 95-100 cm (right flask)

Part VI

Future Work

1. It would be interesting to change the tank inserts (floc hopper geometry) and see how changing the ratio of up flow area to settling area effects the concentration of waste and performance of the system at high turbidities.

2. From our data analysis we found that the effluent turbidity changes with the height of the floc blanket. Process controller is currently not recording the floc blanket height so in order to make these findings we had to record the height from pictures. It would be interesting to have camera configure record the floc blanket height so that we could see continuous data for floc blanket height and effluent NTU.

3. Testing the sludge judge or creating our own version of the sludge judge so that operators can

see what is happening inside the tank. I think a light on a stick is a better idea than a sludge judge because it won't disturb the floc blanket as much.

4. Installing a contact chamber to allow more time for the coagulant and the clay particles to interact before flowing into the flocculate. This should be done at the beginning of the semester so that all the experiments have a contact chamber. Adding one halfway through the semester could add more variation in the data.

5. Conducting more time until formation experiments at lower turbidities would be interesting. We tried to conduct an experiment at 10 NTU and a PACl dose of 0.5 mg/L. We picked the 0.5 mg/L PACl dose by keeping the Coagulant to NTU ratio the same as the optimum coagulant dose for 100NTU which used 5mg/L of PACl.This combination failed to form a floc blanket. It would be interesting to actually form a floc blanket at these lower turbidities.

6. Professor Dick believes that the walls in our experimental set-up are interacting with the particles, affecting settling. To test this, he suggested letting some of our sludge settle in various sized containers to see if the sidewalls have an effect.

Part VII
Method File Explanation

States

1. Floc Blanket Formation
   (a) Run all experiments in this state
   (b) Controls all pumps except for plate settlers, flow rate through plant, and chemical dosing

Set Points

1. Off/On
   (a) Constant; Controls all operational parts of the apparatus
2. On Time Clay Control
   (a) Constant; Controls the amount of time in clay valve is open to generate the raw water
   (b) Value: 2.5 seconds
3. Off Time Clay Control
   (a) Constant; Controls interval at which the clay valve opens
   (b) Value: 5 seconds
4. On Value Clay Control
   (a) Constant; Value between 0 and 1 that sets percent of openness of the clay valve when it is on

    (b) Note: This value is usually at 1, because the tube is small, and keeping it as open as possible reduces clogging

5. Duty Cycle Clay Control
    (a) Variable; Creates a cycle of Set Points (2), (3), and (4) and controls cycle time.
6. Raw Water Min Turbidity
    (a) Constant; Minimum target turbidity of raw water
    (b) In most experiments, this is set at 100 NTU
7. Raw Water Max Turbidity
    (a) Constant; Maximum target turbidity of raw water
    (b) In most experiments, this is also set at 100 NTU
8. Raw Water Turbidity ID
    (a) Constant; Identifies the port for the raw water turbidimeter
9. Raw Water Turbidity
    (a) Variable; Uses raw water turbidity ID to record and report turbidimeter readings
10. On-Off Controller Clay
    (a) Variable that controls clay dispensing
    (b) Uses set points
        i. OFF - controller is off when plant is off
        ii. Duty Cycle Clay Control - controller is on when Duty Cycle Clay Control tells it to turn on
        iii. Raw Water Min/Max Turbidity - controller uses these values to determine whether clay valve should be open or closed
        iv. Raw Water Turbidity - Controller receives raw water turbidity value and turns the clay control off or on based on raw water min/max turbidity
11. Sludge Turbidity ID
    (a) Constant; Identifies the port for the sludge turbidimeter
12. Sludge Turbidity
    (a) Variable; Uses raw water turbidity ID to record and report turbidimeter readings
13. Clarified Effluent Turbidity ID
    (a) Constant; Identifies the port for the clarified effluent turbidimeter
14. Clarified Effluent Turbidity

   (a) Variable; Uses clarified effluent turbidity ID to record and report turbidimeter readings

15. Flow Per Tube Settler

    (a) Constant; This is calculated in Mathcad based on the desired capture velocity in the tube settlers (0.12 mm/sec)

16. Number of Tube Settlers

    (a) Value: 5

17. Total Tube Settler Flow

    (a) Variable; Flow through all tube settlers
        i. Calculated by multiplying set points (15) and (16)

18. Conversion

    (a) Constant; Conversion factor from mL/min to RPM
    (b) Value: 0.36 (mL/min)/RPM

19. RPM Pump

    (a) Variable; Desired RPM
    (b) Flow per tube settler (set point 15) divided by the conversion factor (set point 18)

20. Tube Settler Pump Max

    (a) Constant; Range of RPM's that the tube settler pump can provide
    (b) Value: 590 RPM (RPM can range from 10 - 600 RPM)

21. Tube Settler Pump Control

    (a) Variable that determines the speed the pump (2) will run at
    (b) Value between 0 and 1, calculated by dividing the RPM pump (set point 19) by the Tube Settler Pump Max (set point 20)

22. Flocculator Pump Control

    (a) Variable
    (b) Uses set points (23-25) to set the RPM of the peristaltic pump (0) to achieve the desired flow rate

23. Flocculator Pump Flow Rate

    (a) Constant; Plant flow rate based on target upflow velocity
        i. Calculations for plant flow rate are shown in Sed. Tank Hydraulics Mathcad file

24. Flocculator Pump Tubing Size Code

    (a) Constant; Code for tubing size used in the peristaltic pump (0) to flocculator

25. Flocculator Pump Number of Heads
    (a) Constant; Gives number of tubes running through peristaltic pump (0)
26. Cross-Sectional Area
    (a) Constant; Gives cross-sectional upflow area
    (b) Value: 3.048*10^3 cm^2*s/min
        i. These units are used to yield upflow velocity in the correct units
27. Upflow Velocity
    (a) Variable; Calculated by dividing the Flocculator Flow Rate by the Cross-Sectional Area
    (b) Value: 0.12 cm/s
28. PACl Pump Control
    (a) Variable that uses the PACl pump flow rate (set point 29) and PACl tubing size (set point 33) to control the PACl pump (3)
29. PACl Pump Flow Rate
    (a) Variable calculated by multiplying the desired PACl dose (set point 30) by the ratio of flocculator flow to PACl stock concentration (set point 31)
30. PACl Dose
    (a) Constant; varied by user to coincide with appropriate raw water NTU
31. PACl Stock Concentration
    (a) Constant
    (b) Value: for 100 NTU, typical value is 500 mg/L (Calculations explained in the Parameters section of Methods.)
32. Flocculator Flow/PACl Stock Concentration
    (a) Variable calculated by dividing the flocculator flow rate (set point 23) by the PACl stock concentration (set point 31) in units of (mL/min)/(mg/L)
33. PACl Tubing Size
    (a) Constant; Specifies tubing size for PACl pump
    (b) Value: 16
34. On (Sludge)
    (a) Constant representing when the sludge reaches the maximum height and the pump turns on
35. Off (Sludge)

(a) Constant representing when the sludge reaches the minimum height and the pump turns off

36. Min Sludge Height

    (a) Constant; gives the height at which the wasting pump turns off
    (b) Value: 45 cm from the floor

37. Max Sludge Height

    (a) Constant; gives the height at which the wasting pump turns on
    (b) Value: 50 cm from the floor

38. Floc Sed Interface

    (a) Variable; Height value taken from Camera Configure that gives the height of the sludge in the floc hopper

39. ON/OFF Controller (Sludge)

    (a) Variable that controls sludge removal
    (b) Uses set points
        i. On (Sludge) (set point 34) - when sludge reaches max value and pump needs to remove it
        ii. Off (Sludge) (set point 35) - when sludge reaches minimum height and pump must turn off
        iii. Sludge Min/Max Height (set points 36 and 37) - controller uses these values to determine whether sludge pump should be on or off
        iv. Floc Sed Interface (set point 39) - controller uses reported value to determine whether pump should be on or off
    (c) The function was written to fill a tank (by turning a pump on) when the sensor detects a minimum height. However, in this case, when the sensor detects a minimum sludge height, the pump must turn off. Thus, the off and on controls for the sludge are opposite to those values required as inputs by the function.

40. Waste Pump Flow Rate

    (a) Constant giving waste pump flow rate
    (b) Value: 380 mL/min

41. Waste Tubing Size

    (a) Size of waste tubing pump
    (b) Value: 18

42. Sludge Pump Control

    (a) Uses waste pump flow rate (set point 40) and waste tubing size (set point 41) to set the pump flow rate

(b) Value: between 0 and 1

Part VIII
Experimental Setup Instructions

The Automated Sludge Removal System

Process Controller and Camera Configure software together are able to interpret visual data and control a pump to remove sludge based on its height of accumulation at the floc hopper. An area of interest is set using Camera Configure which is analyzed in order to detect the sludge-water interface and obtain the sludge height. The height is determined based on input parameters for “field of view height” and “elevation of top of field of view”. To determine this information the image processing algorithm takes the average of each row of pixels and its numerical derivative. The smaller derivative obtained determines the point of transition from light to dark, that is, the edge between sludge and water. Then the software converts digital image data to physical length data and stores it as Floc Sed Interface Set Point on Process Controller. To activate the pump a maximum height was defined as a constant Set Point. After the sludge is drained automatically it reaches a minimum depth used as the criteria to turn the pump off again. All Set Points are required by the ON/OFF Controller (Sludge), which controls the removal system. The maximum sludge depth was set to be 50 cm from the floor while 45 cm is the minimum height.

Running an Experiment: The Procedure

1. Create a new folder for the experiment (on the network)
   (a) Make sure the name is unique and descriptive of your experiment
2. Clean Turbidimeters
   (a) Rinse and wipe off with kemwipes and be sure to not get any fingerprints on the vials!
3. Clean Sedimentation Tank
   (a) To remove settled flocs from the sedimentation tank, create a siphon by unhooking the tank from the end of the flocculator
   (b) With the big wooden stick in the corner behind the door, stir up the flocs at the bottom of the sed tank so that they are re-suspended and the jet reverser can pump them out
   (c) Flocs may continue to settle out after you are done siphoning; some flocs in the tank at the beginning of the experiment are okay, but try to get as many out as possible
   (d) To clean the floc hopper, press "Prime" on the sludge pump to make it run as quickly as possible and to suck the flocs into a waste container
4. Clean the Flocculator
   (a) Unhook the flocculator from after where it connects to the pump
   (b) Insert a small piece of sponge into the tubing, then reconnect the flocculator to the pump

(c) Unhook the flocculator from the other end, right before it goes into the sed tank

(d) Start the pump and let the water empty into a large container while the sponge moves through the flocculator

(e) This process creates a lot of pressure, especially if the sponge gets slowed down/temporarily stuck in the connections between pieces of tubing. Be sure that your sponge isn't too big and watch out for leakages due to pressure build-up (these usually occur near the pump)

(f) If the flocculator is still dirty, clean off your sponge and repeat the process

5. Check clay and PACl stocks to make sure there is enough for entire experiment

   (a) Max clay stock concentration = 30 g/L

   (b) PACl stock concentration is currently 1.5 g/3L = 5 mg/L

      i. To make a new PACl concentration, weigh out the desired mass of PACl into a weigh-boat, then mix thoroughly with deionized water (for the sink closest to the door, this comes from the grey faucet on the right)

6. Make sure tank set-up is correct

   (a) All wires connected properly - be sure to check the pumps and the stamp-box connection, as these can become loose rather easily

   (b) The right inserts are in place - see "Changing Inserts" below, for instructions on how to do this

   (c) No flocs in the tank

7. Turn on power strips

   (a) The pumps should all be off, but the stirrers in the clay stock, the raw water tank, and the PACl stock tank should start stirring and the sed tank back-light should come on

8. Start plate settlers - these should be full when the experiment starts

   (a) Fill the tank with clean water from the aerated water supply

   (b) Turn on plate settler pump

   (c) Can run pumps at full speed (use button) to expedite this process, but make sure tank stays full enough by adding aerated water

9. Open camera configure - this cannot be open at the same time as Process Controller

   (a) Make sure the field of view and rotation of the image are correct

   (b) Current camera settings are:

      i. FOV height = 94 cm

      ii. Elevation of top of FOV = 123 cm

   (c) There are other settings you can change, such as exposure time (this will change the brightness of your image). Play around with these a little bit and/or talk to Monroe about them.

   (d) Set the image folder location so that the images will be stored in a unique folder within new experiment folder.

(e) Hit record image. The button should have a bright green triangle on it when the program is set to record and save images

(f) Close camera configure

10. Open process controller

    (a) Select the right method file

    (b) Set to the right directory path (the new experiment folder)

    (c) Adjust for correct PACl dosage, PACl stock concentration, plant flow right, etc – make sure all other variables/constants are correct

11. Turn on floc blanket formation from the drop-down list

    (a) Make sure all the pumps are pumping at the expected speeds, that the influent turbidity is correct, and that the files are being saved to the expected locations. If not, fiddle with Process Controller to fix the problem, or stop the experiment and seek help from your advisor.

    (b) b. Whenever the "state" is changed within Process Controller, new folders will be created for images - the program tacks a number onto the end of whatever you named it originally. This also occurs whenever you open "Edit Rules and States" in Process Controller

12. Come back in a few hours, or as often as coagulant stock needs to be replenished

    (a) Check to make sure that everything is working properly and take note of floc blanket shape, height, and general appearance, as well as the effluent turbidity so that you can discuss your observations with your team members later (especially if something goes wrong at any point)

13. After floc blanket has formed and is stable, process controller can be turned off and closed

    (a) Closing process controller stops the camera from taking more images, otherwise, the camera will keep recording

14. Compress collected images into a video so you can watch the floc blanket form - see "Creating time-lapse videos from images" below

15. Analyze floc blanket formation, sludge concentration/height, turbidity readings, etc. to determine how well the blanket is working. Compare to other results.

Changing Inserts

1. Remove the rubber seal

    (a) This may be tricky, as it is wedged in quite tightly in order to fulfill its role as a seal. There are two holes in the rubber, one at the bottom and one at the top. Use these and the long metal rod with the hooked end to jimmy the seal out. – Feel free to develop your own method of doing this, this is just a suggestion

2. Remove the weir

    (a) Insert the long metal rod through the hole in the top of the weir and pull

3. Remove the big triangle using the hole on the left edge, near the top of the triangle

4. Remove the small triangle (the floc weir base) using the hole on the right edge

    (a) Steps 3 and 4 can be done in any order, whatever is easiest

5. The semi-circle at the bottom of the tank usually does not need to be removed, but can be using a hole on the left edge of the piece.

6. To insert new pieces, start with the big triangle piece, then add the floc weir piece, then the additional inserts, if necessary, and finally add the weir.

    (a) This can be done using the holes in the pieces and the hooked end of the metal rod to guide pieces into place. You may have to use a little force to wedge everything into place, so that everything fits snuggly.

7. The last thing to insert is the rubber seal. This is tricky and takes some persistence, but can be achieved with the metal rod, the holes poked into the rubber, and lots of patience. Again, feel free to think of a better method.

Creating time-lapse videos from images

1. Make sure that all the images of the experiment are in the same folder and in the right alphabetical order.

2. Open the software 'ImageToAVI'. Click 'Add Image Files' to add JPEG files to the compilation list. Select the desired folder and press 'ctrl+A' to select all images. Click OK.

3. Check if the software loaded the image files in the correct chronological order. If it is not correct, click on 'sort list'. An alternative would be to use the 'Bulk Rename Utility' to rename every file using the 'Auto Date' function in the format 'MDY HMS' so that the software 'ImageToAVI' would always load the images in the correct order without the need to sort.

4. Unmark the boxes to maintain aspect ratio and zoom in and set the borders to 0%. Set the pixel format to 32 bit.

5. Click on Output File to name the video file. Type in the amount of frames per second desired (we used 100 fps that gives a time factor of 500). At the bottom of the software it is possible to verify the length of the video.

6. Use the same size of the pictures in pixels for the video (480 width by 640 height).

7. Click on 'Compile images'. Choose 'Cinepak Codec by Radius' as the compressor and confirm.

8. Wait until the video is complete at the Output location.

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[3] Metcalf, Eddy, G. Tchobanoglous, F. Burton, and D. Stensel. *Wastewater Engineering: Treatment and Reuse*. McGraw Hill Higher Education, New York, 4th edition, 2002.