Dashboard / … / Pilot Plant - Pages to be organized

Pilot Plant - Flocculator Research

Created by Sara Elizabeth Schwetschenau, last modified by Rustom L. Meyer on Apr 22, 2009

Pilot Plant - Tapered Flocculation

Author: AguaClara Pilot Plant Spring '08 Sub-Team

Sara Schwetschenau: ses88@cornell.edu

Authors:
Sections on initial Design and Tank Construction were written by:

- Mandy Chu
- Earl James "EJ" Foster
- Kavita Mahulikar
- Carol Serna
- Tamar Sharabi
- Jordan Warner

Sections on the Testing of the Uniform Baffle Configuration were written by:

- Carol Serna

Sections on Testing of the Tapered Flocculator were written by:

- Rebecca Thompson: rnt3@cornell.edu
- Narayana Pappu: nvp4@cornell.edu

Abstract

The Vertical Flocculator Pilot Plant division of the Research and Development team has constructed and is working on testing a turbulent-flow hydraulic flocculator and sedimentation tank at the Cornell University Water Treatment Plant (CUWTP). Prior to the construction of the present tank, flocculation research was done on a small scale, laminar flow tube flocculator. In order to test flocculation under turbulent flow conditions the pilot plant hydraulic flocculator was built. It is a rectangular tank that is divided into three sections that are filled with vertical baffles similar to the baffles used in Honduras.
The vertical baffles were spaced using equations written in a MathCAD program created to test for different velocity gradients, G and amount of mixing, Gθ. An alternative baffle set-up was also created that has varying baffle spacings, where the baffles get farther and farther apart through the tank. The previous setup has a baffle spacing of 6.45 cm with 27 baffles per section. The new set-up is split into four sections with four separate baffle spacings. After preliminary testing, it was determined that the tapered spacing is more efficient and just as affective in a shorter residence time. Settling tubes were designed to measure flocculation performance at different locations in the tank. The effects of changing the parameter Gθ can be easily measured by varying the location of the sedimentation tubes. Our goal for efficient turbidity removal is defined as NTU < 1. Two parallel sediemttation tanks follow the hydraulic flocculator. One sedimentation tank was constructed to learn more about sludge blanket formation and whether or not it is a viable technique for use in our sedimentation tanks. The second sedimentation tank contains lamella and is being used to determine ways that our sedimentation technology can be improved.

Keywords: turbulent-flow, hydraulic flocculator, rapid mix, vertical flocculator, Cornell Water Treatment Plant, velocity gradient, Gθ, efficient flocculation, efficient turbidity removal, tapered flocculation flow control device, sedimentation tank.

Introduction

Since 2004, Cornell University's AguaClara team has worked in conjunction with Engineers for a Sustainable World (ESW), and Agua Para El Pueblo (APP)to design and build four water treatment plants in Honduras. In addition to providing clean water to La 34 and Ojojona, a plant in Marcala is under construction and a design for a plant in Tamara is also being completed. The plant at Ojojona also functions as a pilot operation, demonstrating successes and potential problems for future plants.
The R&D team focuses on optimizing flocculation technologies to make them more efficient and effective. Multiple sub-teams

work on this task, each using a unique approach. The lab sub-team runs bench-scale experiments in the AguaClara lab, using a tube flocculator that operates in the laminar flow regime. In spring 2007, the Vertical Flow Pilot Plant sub-team worked with various Cornell University staff to design and build a larger-scale vertical flow flocculator at the Cornell University Water Treatment Plant (CUWTP), to facilitate testing under turbulent flow conditions. The new flocculator more closely models Ojojona's existing configuration, hopefully allowing for more practical testing. This experiment will also allow verification and possible reduction of the large Gθ range (20,000 to 150,000) recommended for community-based flocculation. Flocculation effectiveness is influenced by a number of factors, including coagulant dosage, mixing value, influent turbidity and velocity gradient. The team hypothesizes that the velocity gradient is the central variable for optimizing flocculation.
After construction of the plant was completed at the end of the Spring 2007 semester, during the summer testing was done on the uniformly spaced baffles. Then in the Fall 2007 semester the uniform baffle spacing set-up was exchanged for a tapered baffle configuration. The Spring 2008 semester is going to be spent doing more extensive testing on the tapered set-up.
Initially the main goal for the Fall 2007 semester was to do research on the tapered set-up in order to learn more about where flocs were breaking up in the flocculator. Research over the summer was focused on several areas of the interest with this test flocculator. First, it was desired to determine a floc formation and floc break-up profile through the flocculator. This would help in the determination of the different aspects of the tank that were either helping or hindering flocculation. Secondly, there was a focus on determining the optimum alum dose based on raw water turbidity for ideal floc formation. This test was designed to help in the design of a better alum dosing algorithm. After the summer ended, the overall goals of the flocculator changed, attention shifted to the set-up and design of the flocculator itself.
Experiments and theory were leading to the conclusion that good floc formation would require an average velocity gradient that changed throughout the flocculator. Thus the Fall 2007 semester's focus switched to the design and construction of a tapered baffle set-up. The testing of this tapered set-up was planned for the Spring 2008 semester, performance will be compared to the previous baffle arrangement. The overriding goal is to determine which set-up is more effective and efficient at creating large flocs.
Research done on other sub-teams determined that the highest values of G were in the 180 degree bend and that the majority of flocculation was happening in these turns. The channels themselves seemed to be doing little to further flocculation. Thus the average velocity gradient that were being used in calculations were not actually an accurate representation of the actual gradients that are occurring in the tank. Thus floc break could be occurring in the turn arounds, because of an under estimate of the velocity gradient. The next step was to increase the G values in the channels to levels that were closer to those found in the turn arounds, essentially decreasing the variation in the gradient throughout the flocculator, and thus making the average gradient a more accurate representation of what was happening in the tank. A preliminary idea was to add some sort of obstacle structure to the channels to increase G. An initial design of interconnected PVC pipes that would be suspended in the channels between baffles creating higher shear levels and thus a higher velocity gradient.

Methods

There have been three major phases in research with the pilot plant. The first phase was the initial design and construction of the tank and the uniformly spaced baffles. The second stage was the testing of the uniformly spaced baffles that resulted in some tank modification. Third stage was the construction of the tapered baffles configuration. In the third stage this initial design of uniform baffle spacing was to be compared and contrasted with the tapered design, having a different G distribution. In this alternative configuration, the velocity gradient (G) was gradually decreased along the flow path by widening the baffle spacing. A plan for a future design was to add small obstacles between baffles, to even out the difference in gradient between the turn arounds and the channels. Initially a high G is used to maximize floc formation. Then G is gradually decreased in later sections to minimize breakup of large flocs. It is hypothesized that larger and better quality flocs will be formed in the latter tapered configurations. The current stage is testing this tapered baffles set-up and making additional tank changes based upon results.

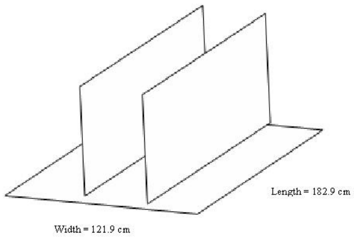
Pilot Plant Construction and Baffle Design (Uniform Spacing)

Unknown macro: {float}

Plastic Tank that was the starting design constraint for the vertical flow hydraulic flocculator.

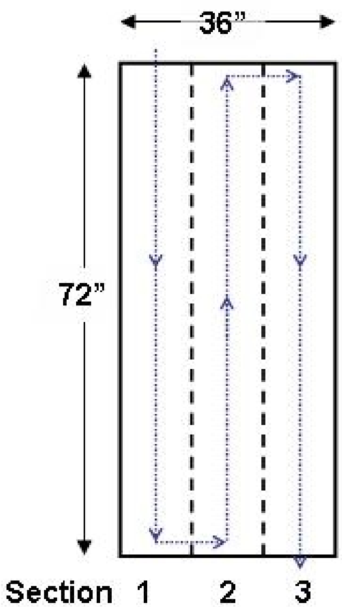
The construction of the tank was started during the Spring 2007 semester. The floc tank was designed to be contained in a polyethylene tank of dimensions 182.9 cm × 91.4 cm × 121.9 cm (length × width × height) with a wall thickness of about 0.8 cm.#tankThe design goal was to divide the tank into 3 separate sections, basically condensing a long, narrow flocculation tank into a more compact space by snaking the flow back and forth. The initial design divided the total minimum mixing value (20,000) evenly among the three sections, with each section having an even velocity gradient (G) of 45 s-1.

Unknown macro: {float}



Plastic dividers that create three sections for a serpentine flow path through the tank.

Unknown macro: {float}



The serpentine flow path can be clearly seen in the top view of the flocculator.

In order to divide the tank into three sections, a divider system had to be built in the tank. Originally it was planned to purchase two plastic sheets to function as the dividers and weld them vertically into the tank. This option was soon rejected due to two major concerns: difficulties of welding inside the cramped spaces of the tank, and lack of strength in the welds. After much contemplation, the maintenance shop proposed a plan to build a structure that would provide support and flexibility. The sketch shows that the #dividerswere welded onto a base slab and the completed module was placed into the tank. A port hole (hole through which water flows between sections) was cut in each divider prior to welding. The dimensions of the dividers are approximately 182.9 cm x 121.9 cm with a 0.6 cm thickness. The choice of material for the dividers as well as the base slab is high-density polyethylene and was specifically chosen for its non-reactive property in water treatment process, and most importantly its ability to be welded.
Below is a list of fixed parameters (or "givens") and the values of G to be used in the initial setup.

Givens:

- Tank dimensions: 182.9 cm × 91.4 cm × 121.9 cm
- Tank wall thickness: 0.8 cm
- Tank divided into 3 sections (serpentine flow path)
- Total minimum mixing value (Gθ) = 20,000
- Initially 1st, 2nd, and 3rd sections of tank to have velocity gradient (G) of 45 s-1

Variables:
With initial design constraints defined, a MathCAD program was used as a design/calculation tool to determine variables.

- Flow rate- Q
- Number of baffles per section- n
- Baffle spacing - b
    - Baffle dimensions:

- Width x height
- Different heights for top and bottom baffles)

- Dimensions of openings in dividers

- Width x area of flow path

- Total head loss- h
- Water level- L

Calculations:
The purpose of adding baffles was to increase mixing (G) by acting as an obstacle and forcing water through a restricted flow-path. G is a variable that controls the upper limit of shear. There is a maximum G (and thus a maximum shear) that a floc can experience before being broken up. The value of G directly controls the baffle spacing needed for efficient floc formation and preservation. A flow rate of 120 L/min and an effluent depth of 76.2 cm were chosen for baffle configuration design. Presented below are the equations and values used for design calculations.

- Baffle Design
  Total minimum mixing value (Gθ = 20,000) is a function of path dimension and residence time. The equations used to calculate baffle spacing are presented below:
  $$G = V^{\frac{3}{2}}\sqrt{\frac{1}{2\nu L}}\sqrt{(\sum K_{\min} + f\frac{L_s(w+b)}{2wb}}$$
  $$b = \left(\frac{1}{G\max}\right)^{1/2}\left(\frac{Q}{w}\right)^{3/4}\left(\frac{K}{2\nu}\right)^{1/4}$$ Variables:
  where
- G = velocity gradient
- V = flow velocity through the channel
- v = viscosity of water
- Kmin = 3 × (number of 180 deg turns)
- f = corresponding friction factor f(Reynolds number, material)
- L = flow depth (water level)
- Ls = shear length = water level - 1.5b
- w = 1/3 the tank width, and
- b = baffle spacing

Since both V and f are functions of baffle spacing (b), the above equation cannot be solved explicitly, and thus multiple iterations were employed in MathCAD to solve for b within a 1% error tolerance. The resulting b value for the first configuration with identical G (45 s-1) is 6.45 cm with a total headloss of 11 cm. Given these b values and the corresponding flow velocity (V), the below equations were then used to calculate the number of baffles in the each section:

$$\theta_{\text{section}} = \frac{(G\theta)_{\text{target}}}{G_{\text{section}}}$$

$$n = \frac{\theta_{\text{section}}V}{L}$$

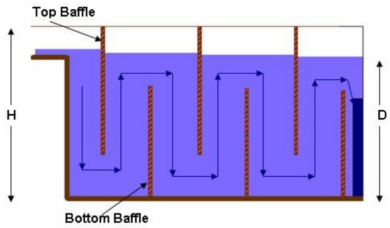
The number of baffles - n - that was calculated for each section was found to be 27.
After the spacing and number of baffles was designed next was the height of the baffles. The baffles needed to be large enough to control the flow of the water and produce mixing. However, if they were too large the turning radius of the water would be small and create unwanted shear, which could break up flocs. To control this, the flow expansion around the turn of the baffles needs to be large enough to minimize unwanted shear. In order to do this, a flow space of 1.5b × w is required. Here w is the width of one section of the flocculator. The equations below were used to determine the dimensions of both types of baffles. The two types of baffles are top and bottom baffles.

$$\text{Max.TopBaffleHeight} = H - 1.5b_3$$

$$\text{Max.BottomBaffleHeight} = H - headloss_{\max} - 5cm - 1.5b_3$$

The figure shown below shows what is considered a top and bottom baffle.

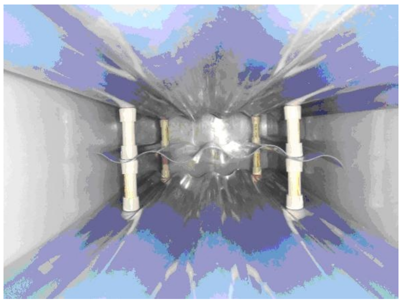
Unknown macro: {float}



Side view of the baffles. Top and Bottom baffles and flow path can be clearly seen.

The resulting fabrication height of top baffle is 88.9 cm while that of bottom baffle is 71.1 cm.

Unknown macro: {float}



Corrugated Baffles spaced and connected with the cpvc caps and pipes. Pressure connection holds baffles together.

The baffles are cut from plastic corrugated roofing material which can be purchased at most local hardware stores such as Lowe's and Home Depot. It is cheap, accessible, and very similar to the material used in Honduras.
Since baffle design and dimensions depended on the divider design, baffles were not cut until the dividers #dividers were installed. Baffle #bafflesdimensions were determined to be approximately 88.9 cm × 30.5 cm for the top baffles and 71.1 cm × 30.5 cm for the bottom baffles. Baffles were cut slightly wider than the section width (30.5 cm). This was done to tighten the fit of the baffles, provide support for the dividers, and to prevent leakage of water between the baffle and the tank walls.
Baffles were attached as a contiguous unit for each of the three sections and then slid into the proper section. To assemble these units, plastic caps were screwed into four locations on each baffle. Short lengths of PVC pipe were fitted into the caps. The arrangement is shown below in Figure 10. This design has various advantages. First, it allows for relatively easy assembly. It also allows for easy disassembly, which means that it is easy to take apart the units to change baffle spacing by adding shorter or longer pipe sections. The design also decreases the amount of material used. To achieve the baffle spacing of 6.4 cm we cut connecting pipes to about 5.3 cm, accounting for the thickness of the caps. A band saw was used to cut the pipes at this dimension. A lathe and a mill were both used to bore ¼" holes into the caps.
Four different ¼" (0.6 cm) screw holes had to be drilled into each individual baffle at the location of the connectors. To position the holes we placed one top baffle on a bottom baffle and marked the desired location at the center of the nearest concave to improve accuracy and get a clean cut. The average position is about 2.5 cm from the top and 2.5 cm from the side for those holes at the bottom of the bottom baffles.
To move from one section to the next, water must travel through a port in the divider. The dimensions of these ports were determined with the following equations:

$$PortSize_1 = 1.5 \times \mathrm{w} \times \mathrm{b}_1$$

It should be noted that here w indicates the width of one section in the tank. (about 1ft)
To avoid short-circuiting of flow, the ports were cut in rectangular shape of lesser width than the corresponding baffle spacing for that section.
Excess pipe material (standard schedule 40 pipe) from the rapid mix unit was used to build the outlet pipe. The turns were composed of two elbows joined at the ends by a small cut of piping. Each length of pipe for the rapid mix was about a meter in length to provide the 2 m flow length. A sanitary tee-fitting serves as the inlet of the unit.
Note: All text in blue is currently under revision.
The operational effluent flow depth was set to 96.5 cm to ensure the flow over the bottom baffles would not cause floc break-up because of high shear levels. A MathCAD program (N:\Research and Development\Vertical Flocculator PPT\AutoCAD\Flowrate trouble-shoot (identical G).mad) was made to understand how the manipulation of G and Gθ can be achieved by altering Q. As both G and Gθ are functions of head loss (hl) and hydraulic residence time (theta), two sets of equations (for computing hl and theta) are used to assess their values. Total head loss can be separated into major and minor loss. Minor loss is a function of the friction factor (f), which can be obtained from the Moody's diagram for a known Reynolds number. For this particular baffle configuration, major loss only makes up for less than 1 cm of the total head loss (11 cm);

majority of total head loss comes from corner-turning which is accounted for by minor loss.

$$headloss = \left(\sum K + f \cdot \frac{L}{4R_h} \right) \frac{V^2}{2g}$$

$$R_h = \frac{w \cdot b}{2 \cdot (w + b)}$$

$$K = \frac{\sum K_{\min or}}{n}$$

This equation was solved for Kminor. The following set of equations listed below is used to compute theta, and thus G and Gθ along with the previously calculated head loss of this configuration.

$$Vol = (EffluentDepth + 0.5h_l) \times 3w \times Length_{\text{tank}}$$

$$\theta = \frac{Vol}{Q}$$

$$Gaverage = \sqrt{\frac{g \cdot h_l}{\nu \cdot \theta}}$$

All the equations described above were input into the MathCAD program for generation of the graph in the graph which dictates the exact relationship between Q and G and Gθ. #Q,G,Gtheta graph

Unknown macro: {float}

Unable to render embedded object: File (Graph - G, Q , Gθ.jpg) not found.

Graph of the relationship between flow rate, velocity gradient and mixing factor (Gθ) for the uniform baffle spacing.

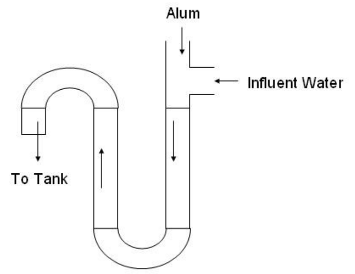
Our initial experimental condition was to test flocculation at G of 45 s-1. According to graph above a flow rate of 138 L/min is required to attain a G value of 45 s-1. With this flow rate applied, however, Gθ will greatly exceed the original estimate of 20,000 at the tank outlet, instead reaching a value of 34,170 for Q = 138 L/min. A different function was programmed in the same MathCAD file mentioned in the previous paragraph to re-estimate the new location of where Gθ = 20,000 is reached in the tank. Knowing the values for the target Gθ (20,000) and average G (45 s-1), adjusted reactive volume can be computed with the equation below. To assess this volume change in terms of tank length, see the appropriate equation below. Location value indicates the new sampling port location measured from the influent end of tank. For this particular design, the sampling tube would have to be placed 320 cm (Location = 320 cm) in the flow-path away from the influent end of the tank to measure a turbidity value for Gθ = 20,000. In other words, since one section of the tank is 182.9 cm long, this sampling port would reside at 137.1 cm from the flow-entry end of the 2nd section in order to measure turbidity for a Gθ of 20,000.

$$Vol = Q \times \frac{G\theta_{\text{target}}}{\overline{G}}$$

$$\Delta Location = \frac{Vol}{(EffluentDepth + 0.5h_l) \times w}$$

Design and Construction of Rapid Mix Unit

Unknown macro: {float}



Schematic of the Rapid Mix Set-up. This configuration was designed and constructed in Spring 2007. It should be noted that in the Spring 2008 semester the main tube was lengthened to accommodate an entrance tank.

A total Gθ of 1000 was estimated to be the required mixing in the rapid-mix unit in order to completely blend the alum with the inflow water before entering the tank. This is done to ensure that the clay and alum are well mixed and the two types of particles are in close proximity to allow efficient collision and adhesion to occur along the flow path in the tank. The initial design was based on only having a 3-inch inner diameter (I.D. = 7.6 cm) PVC pipe. The following equations were used to determine the number of 90degree turns and required path length to achieve the desired Gθ.

$$V = \frac{Q}{A}$$

$$G = V\sqrt{\frac{1}{2\nu\theta}(\Sigma K_{\text{minor}} + f\frac{L}{2R_h})}$$

$$\theta = \frac{L}{V}$$

$$R_h = \frac{D}{4}$$

where:

- Rh = wetted perimeter
- D = pipe diameter
- A = flow-area
- L = path length
- f = friction factor
- Kminor = number of 90 degree turns × 0.3

These calculations yielded a flow path (L) of 2 m with 4 90 degree-turns. #rapid mix unit shows the configuration of the rapid-mix unit.

Testing of Uniform Baffle Configuration

After the completion and installation of the flocculation tank in the water treatment plant, tube settlers are used to test effluent turbidity at different locations. The tube settlers were designed to mimic the sedimentation tank that would traditionally follow the flocculator. Tube settlers were chosen because they provide an inexpensive way to sample and create a minimal disturbance within in the tank. Using this method, different locations of the tank can be sampled. Data gathered can be used to assess how each stage of the tank is affecting the final effluent turbidity. The tube settlers were designed using the following equipment.
Equipment:

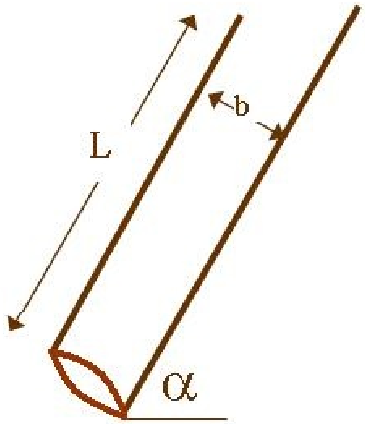
- Glass tube settlers (3)
    - Length: 60 cm
    - Diameter: 2.5 cm
- Peristaltic pump
- Turbidimeters (3)

Once the equipment was gathered, the next step was to design the flow rate for the peristaltic pump. The following assumptions were used in the calculation for the flow rate:
Assumptions:

- The optimum angle for tube settler is 60°
- The critical velocity is 10 m/day

Sixty degrees is used because it is the angle at which the distance required for floc settling is minimized and still allows the solids that settled on the side of the tube to slide down. The critical velocity is taken from a range of accepted values and has been found to be the critical velocity in previous plants in Honduras. The flow rate was calculated using the following equations.

Unknown macro: {float}



Schematic of the Data Collecting Settling Tubes.

Dimensions and Variables chosen:

- b = diameter = 2.5 cm
- L = length of the tube settler = 60 cm
- alpha = optimum angle = 60°

$$Q = V_\alpha \times \frac{\pi b^2}{4}$$

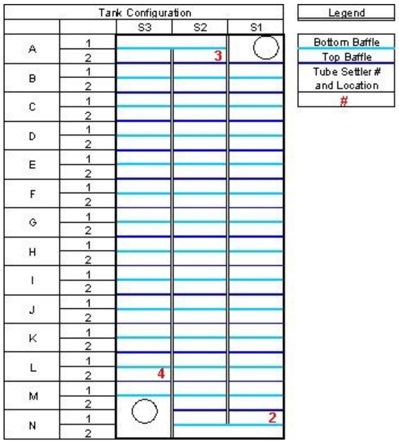
$$V_\alpha = V_c \left(\frac{L}{b} \cos\alpha + \sin\alpha \right)$$

The following equations were adopted from Shultz and Okun for determining critical velocity for up flow through a tube. The flow rate calculated for our initial configuration was 44 mL/min. There is a linear relationship between pump speed and the flow rate through the settling tube. The flow rate though the settling tube also has a linear relationship to the critical velocity of the sedimentation process in the tube. It is important to note that the critical velocity of the settling tubes is the same as the critical velocity that can be found in the sedimentation tanks at Ojojona.
The setup of the tube settlers in the tank was the next design step. Originally the tube settlers were to be hung from the edge of the tanks at designated locations. On further inspection however, when laid between the baffles on top of the connectors they are at the correct angle and so can easily be relocated and do not require any attachment to the tank. The final design consists of the tube settlers nestled between the baffles, and then connected to the peristaltic pump. The peristaltic pump pulls water from the peristaltic pump at the correct velocity and the water is routed through a turbidimeter in order to measure the turbidity. Also installed is a turbidimeter that measures the influent turbidity of the water before it reaches the tank. This turbidimeter is gravity fed.

Data Collection

Process Controller was used as our main data collection tool. MathCAD programs were then used to analyze the data that was collected. Process Controller is a software package that is used to control the raw water pump, the alum pump and data collection. For the raw water pump Process Controller only controls the on/off status of the pump. When the flocculator is running the raw water pump is turned on and the flow rate is controlled by a valve that can only be changed in increments. The flow rate was calculated by partially draining the flocculator to below the outlet pipe height. The valve was then opened to a noted location and the time it took for the water to rise 5 cm was recorded. To calculate the flow rate increase in the volume of water in the tank was divided by the time it took for that volume to fill in the tank. The volume was calcuated by multiplying the height the water rose in the tank by the cross sectional area of the tank. When this technique was used the head loss over the flocculator was small and did not affect the measurement. If the head loss increases then a new way to measure the head loss will need to be created.

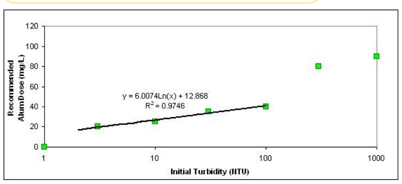
Unknown macro: {float}



This choice of location for the tube settlers was chosen originally to establish general information about how flocs were forming in each individual section of the flocculator.

The states utilized by process controller allow the flocculator to run continuously and data to be collected about how alum dose and changes in Gθ affect flocculation and settled water turbidity With the configuration of the baffles spaced evenly throughout the flocculator G remains constant through the 3 sections. However, by sampling at different locations the volume of the flocculator that the water travels through changes which changes θ and thus Gθ. The tube settlers were placed one at the end of each section. #Original Tube settler set-upThis figure shows the configuration that was originally tested and used to collect data. This configuration was chosen to get a general understanding of how each section contributed to floc formation and final settled water turbidity.

Unknown macro: {float}



The graph shows the data and derived equation for optimal alum dose based on raw water turbidity.

The alum dose currently being used is an equation derived from data that was collected and analyzed by students working on the AguaClara project through CEE 453 during spring 2005 (Wilson and Rog , 2005). It utilizes a log relationship and is shown below, the equation is included in the figure (#Alum Dose Equation). The equation is only relevant for turbidities under 100 NTU, at higher turbidities another relationship will need to be derived. The general form of the equation is Y = A + B*log(NTU) where A and B are fit parameters, and typically set to both be 15.
In order to investigate alum dosing further, Process Controller was used to cycle the alum dose from 0 mg/L to 30 mg/L in increments of 5 mg/L. Each increment was run for two residence times of the flocculator. The residence time of the flocculator was calculated using a flow rate of 114 L/min and the equations below.

$$Vol_{TubeSettlers} = \pi * \left({}^{D}\!/_{2} \right)^2 * L$$

$$\theta = \frac{Vol_{TubeSettlers}}{Q}$$

The first residence time was to establish a stable environment and ensure that the water being sampled was using the alum dose being recorded. The second was time during which the data that was analyzed was collected. During these tests tube settlers were left in specified locations. Unless there was a rainstorm or some other large disturbance the raw water turbidity remains relatively constant. It is hoped that this setup will allow the impact of different alum doses to be seen at a specific Gθ and turbidity.
The values for G (45 s-1) and Gθ (20,000) were calculated at a plant flow rate of 120 L/min. With these design parameters in mind it was calculated using the head loss equation show below that there should be a head loss of 11 cm from the inlet to the outlet.

$$headloss = \left(\sum K + f \cdot \frac{L}{4R_h} \right) \frac{V^2}{2g}$$

Unknown macro: {float}

Schematic of the placement and and purpose of the tubes used to measure head loss across the tank.

In order to get a more accurate reading of measured head loss two holes were drilled into the lower part of the tank and a tube connected to the holes. The tube acts as a manometer and the water in the tube reaches the same height as the water in the flocculator at the position of the hole. #head loss measurement
The tube can be moved to different locations around the outside of the flocculator and still maintains the height of the water at the position of the hole in the flocculator. The water level in the tube can be compared to the water level at almost any position in the flocculator. Since the change in water level is so small this allows a more accurate measurement than simply measuring the height of water at each location and helps to minimize error.

$$\sum K_{\min or} = \left(\frac{h_l * 2 * g}{V^2}\right) - \left(\frac{n * f * L_s * (w + b)}{2 * w * b}\right)$$

$$K = \frac{\sum K_{\min or}}{n}$$

Variables:

- Width of section (w, cm)
- Baffle spacing (b, cm)
- Head loss (hl, cm)
- Number of baffles - n
- Baffle length (L, cm)
- Velocity (V, m/min)
- Friction factor (f)

Using the manometer method, with a hole at the inlet and a hole at the outlet, the measured head loss can be used to find G, Gθ and K can be back calculated. The equations above where used to back calculate to find the head loss coefficient K.

Design of the Tapered Baffles Configuration

The first step was to determine a theoretical relationship of how Gθ and Gmax are related. Our baffle set-up was developed so that our values of Gmax and Gθ remained below the theoretical curve. The theoretical curve that was used can be seen below:
The region from 0 to the maximum Gθ was divided into a specified number of equal sections that would be present in the flocculator. For this set-up it was decided to create four sections. The corresponding Gmax values were then read off of the graph.

Construction of the Tapered Baffles Configuration

The tapered baffles set-up that was the result of new research about velocity gradients in the tank was done during the Fall 2007 semester. The baffle set-up was made using the same materials and with the basic construction design as the previous set-up. Caps and piping were used as the connection holding the baffles a set distance apart. These caps and the pipe were made of CPVC material. The caps were attached to the baffles by #6-32 stainless steel ½ inch screws and nuts. These screws placed through a ¼ inch hole that was drilled in one cap and then through a hole in the baffle and then through another cap. The hole in the baffle what about ¾" wide but this was an error in construction the hole should be the same size as the holes drilled in the caps, ¼". The nut was screwed on to the other end of the screw to keep the structure and ensure that the caps stayed firmly attached to either side of the baffles. Each baffle contained four connections. It was thought that four places of support on the baffle should give the material enough structural support to hold each baffle perpendicular to flow.

The baffles were made out of blue transparent corrugated plastic roofing material. The size of the baffles was determined based on the water level and necessary baffle spacing at the end of the tank. The distance between the water level and the top of the bottom baffle or the height between the bottom of the tank and the top baffle was kept the same through out the tank. This distance was taken as the spacing in the last section times 1.5, resulting in a turnaround of 15.1 cm.

The 20 upper baffles were cut to be 31cm wide by 88 cm long. The 19 lower baffles were cut to be 31cm wide by 62cm long. The values for the baffle spacing and number of baffles per section can be seen in the table below.

Section	N (number of Baffles)	B (baffles spacing)	Pipe Cut Length
1	2	3.339 cm	2.239 cm
2	4	3.952 cm	2.852 cm
3	5	5.794 cm	4.694 cm
4	28	10.071 cm	8.971 cm

Table 1: The above table contains the exact values for the baffle spacings, number of baffles and length of the pipes connecting the baffles for each individual section.

The main difference between the previous set-up and the current set-up is that instead of having the spacing be uniform across the entire flocculator, a tapered spacing that was found above was used. The baffles were also cut ½ cm wider than for the previous set-up. This was done to help create a better seal so that less short circuiting will occur through out the flocculator. The wider baffles also help stabilize the slightly flexible section dividers. Although the wider baffle did help these issues upon observation the section support structure that was put in place over this past summer was still necessary to provided added support.

The design described above produced a flocculator that was two thirds the size of the previous flocculator, taking up two sections of the divided flocculator. The flocculator was set-up so that the baffle structure was placed in the first two sections of the flocculator and data was only collected from these sections. The final section was left with the old set-up in it just to fill the space and help keep the dividers from bowing. This section was not tested, and was just used to fill the tank until the water reaches the exit pipe at the end of the third section. In future set-ups it is hoped that this third section can remain empty and then can be used as sort of sedimentation tank to perform further research on this project.

Theory of Tapered Baffle Configuration

The first step in designing the tapered baffle configuration to determine a theoretical relationship of how Gθ and Gmax are related. Our baffle set-up was developed so that our values of Gmax and Gθ remained below the theoretical curve. The theoretical curve that was used can be seen below.

Unknown macro: {float}

[!Pilot Plant^G,GθCurve.jpg|width=200px!|Pilot Plant^G,GθCurve.jpg]

This curve shows the theoretical relationship that is believed to exist between G, the maximum velocity gradient and Gθ the mixing parameter.

The region from 0 to the maximum Gθ was divided into a specified number of equal sections that would be present in the flocculator. For this set-up it was decided to create four sections. The corresponding Gmax values were then read off of the graph. The values for Gmax are larger than the curve because for our original model the assumed the energy dissipation length in the channel was assumed to be b, the distance between two baffles. This parameter was altered in a later model and thus our values appear to be larger than the theoretical curve. These values were also the result of working backwards. Gθ values were found by rearranging the equation that was used to find the number of baffles in each section. The number of baffles was multiplied by the residence time for one baffle and then multiplied by the value of Gaverage for that section. These values can be seen in the table below. These numbers are a bit odd because Gθ should be increasing through the sections. I believe that these numbers are off because of the changes that were made to the model and the attempt at back calculating. Values of Gθ from a new model were given below.
Typically when using the model properly the Gθ values would be found arbitrarily by dividing the range of the Gθ values from the curve by the number of sections chosen for the design. Gθ values found with this method using the new model are also listed in the table for comparison.

Below are listed the know values for the flocculator:

- Q=100L/min - plant flow rate
- w= 1ft - width of the flocculator
- K=0.3 - minor loss coefficient for 180 degree turn arounds
- nu = 1x10-6 m2/s - kinematic viscosity of water
- h=76.4cm - the approximate height of the water in the tank.
- mu = 0.12mm roughness coefficient

- Values for Gmax can be seen in the matrix below and they are split up by section. Gmax represents the maximum velocity gradient that is seen in each section.

Parameter	Section 1	Section 2	Section 3	Section 4
GMax (1/s)	444.185	317.075	147.516	48.826
Gθ	5.186x10^4	3.981x10^4	2.197x10^4	9.407x10^3
Gθ New Model	3.245x10^3	7.044x10^3	1.047x10^4	2.022x10^4
Theta (s)	3.888	4.601	6.746	11.726
GBar (1/s)	133.583	102.535	56.587	24.23

Note: The version of the model that we built was altered after we had created the baffle set-up, but before the report was written so some values from the model were lost. If these values were needed they were back calculated from the values we had and using the model's equations. The only values where this was done were for The Gmax and Gθ values for individual sections.

Baffle Spacings

The baffle spacing needed to attain these levels of Gmax was then determined using the following equation.

$$b = \left(\frac{1}{G\max}\right)^{1/2}\left(\frac{Q}{w}\right)^{3/4}\left(\frac{K}{2\nu}\right)^{1/4}$$

After the baffle spacing for each section was determined. The number of baffles for each section was then found using the theoretical graph again. First, the residence time for one baffle section was determined using the flow rate of the plant and the volume of one baffle spacing. This calculation was computed for each of the four specified sections. The residence times for one baffle in the individual sections are listed in the table of above. The equation calculating the residence time for one baffle is listed below.

$$\theta baffle = \frac{b \cdot w \cdot h}{Q}$$

The next design step was to find the number of baffles that were found in each section. Basically this was done by using the theoretical value of Gθ for each section and then diving by the Gθ value calculated for one baffle in that section. This number was then truncated to make it an integer. Truncation was used over rounding to ensure than that all values of Gθ used would fall below the theoretical curve.

Unable to render {include} The included page could not be found.

Gaverage is the average velocity gradient found in each section.The lowest Reynolds number found for this flocculator was found in the fourth section and was 53,000 this is well into the turbulent range. So turbulent flow is confirmed and the appropriate equation for friction factor was used. The friction factor for all sections was found to be 0.047. The subsequent series of equations represents the chain of substitutions that results in the final equation used for G average. Values for G average can be found in the table above.

$$Gaverage = \sqrt{\frac{g \cdot h_l}{\nu \cdot \theta}}$$

$$headloss = \left(\sum K + f \cdot \frac{L}{4R_h}\right)\frac{V^2}{2g}$$

$$\mathrm{Re} = \frac{Q}{R_h \cdot \nu}$$

$$R_h = \frac{w \cdot b}{2 \cdot (w+b)}$$

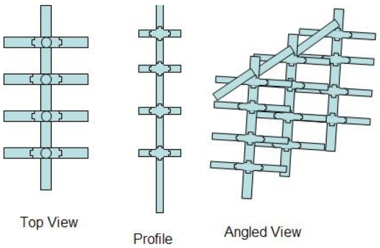
$$\mathrm{f} = \frac{0.25}{\left[\log\left(\frac{\varepsilon}{3.7D} + \frac{5.74}{\mathrm{Re}^{0.9}}\right)\right]^2}$$

The MathCAD program written performed the calculations described above and out putted the following values, baffles spacing, number of baffles, tank length, total head loss and Gheta and Gmax for all sections specified. These outputs were then used in the final construction of the tapered baffle set-up that was added to the pilot plant.

Inline Obstacles

MathCAD was used for this portion of the design as well. The basic idea for this was that the obstacles are added to help even out the velocity gradients throughout the flocculator. The flocculator is design around what the gradients are for the 180 degree turn-arounds at the top and bottom of each baffle, but the gradients in the channels between the baffles are typically much lower and thus flocculation is not occurring as efficiently as it could. With the addition of these inline obstacles we hope to increase the velocity gradients in the channels between the baffles and thus encourage flocculation similar to what occurs in the bends.

Unknown macro: {float}



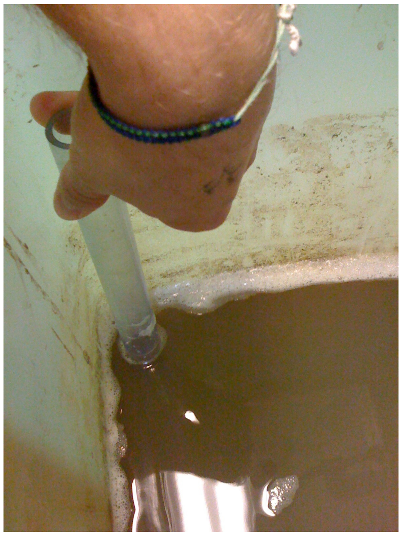
Schematic for the construction of the inline obstacles. These obstacles are designed to increase velocity gradient levels in the channels.

Cylinders placed perpendicular to flow were thought to be the most effective. See the figure below for details on the design and placement of the obstacles in the flocculator, which are to be built and implemented this upcoming semester.
The obstacles will be constructed of PVC. The long pipe seen in the Top View will run along the length of the tank. It will lay on top of the baffles, perpendicular to them. The longer pipe seen on the Side View will be hanging down vertically from the pipe lying perpendicularly across the baffles. The horizontal bars seen on the Side View will be connected by tees to the longer pipe in the Side View. The horizontal bars will be perpendicular to the flow path of the water through the baffles.
The number of obstacles in each baffle spacing in each tapered unit still needs to be determined, but we hope that this design will prove effective when it comes time to construct the flow obstacles.

Testing and Tank Modifications

The first half of the Spring 2008 semester was spent making significant modifications to the flocculation tank. When the tapered configuration was put into the flocculator the baffles around the port holes were set farther apart than in the original configuration and thus the port holes had to be enlarged to ensure flocs were not being broken up. The holes were enlarged so that the port hole area is equal to the area of the rectangle below a top baffle. Sludge that had settled to the bottom of the tank was removed and tank was cleaned before it was started for the semester. Additional sand was re-added to the bottom of the tank before the baffles were placed in. The sand was added to hopefully create enough head loss in the space between the bottom panel and tank wall. The sand was also added to hopefully reduce bypass of water underneath the baffles. When the tank was turned on it was determined that a significant amount of flow was still by-passing the system and flowing under the bottom panel, despite the several inches of sand that were added to the third section, which is supporting the section dividers. It was noticed when the tank was filled that that the first and third sections were filling at all most the same rate. Before caulking was done additional sand was added to the bottom of the tank in the third section to try and see if significant enough head loss could be created in the tank to cause most of inflow to follow the correct flow path. Upon refilling the tank the upflow was still noticed. When a clear PVC tube was shoved down into the gap and the difference in water height in the tube and in the tank was measured. It was found to be about ¾". This was deemed significant and caulking was deemed necessary. The tank was drained, cleaned and dried of sand again so that caulk could be added to seal the gap.

Unknown macro: {float}



Testing procedure for determining the up flow velocity around the bottom panel of the flocculator.

While the tank was off to caulk the bottom it was decided to implement several other changes at the same time. A digital flow meter was added to the inlet pipe. This meter was put in place for several purposes. First, it was added to make it easier to alter the plant flow rate without draining and refilling the tank to determine the flow rate. Secondly it was added to provide instant feed back to the flow measuring bucket that was added to the inlet of the tank.

Unknown macro: {float}

Picture of the raw water inlet into the tank before the modifications were made to accommodate the bucket.

The structural changes needed to be implemented the flow measuring bucket were also implemented while the tank was off. These changes included building a brace and stand for the bucket to sit over the tank, above the first baffle. In order to accommodate the bucket the rapid mix tube had to be cut and extended so that instead of flowing directly into the tank it flowed into the bucket and then the bucket's weir deposited water into the tank. Alum inlet also had to be extended upward because after the rapid mix extension the alum was entering lower than the raw water inlet pipe and this could cause back flow down the alum tube not to mention leaking in this part of the rapid mix set-up that was not glued down.

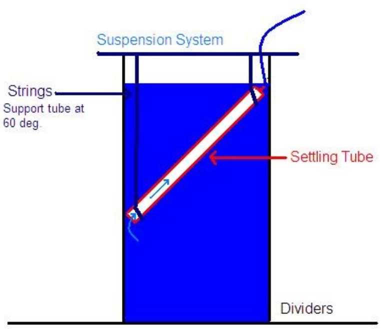
Unknown macro: {float}

The raw water inlet after structural modifications were made to the rapid mix tube and bucket was in place.

In the Summer of 2008 the spacing of the final section of the flocculator was altered to reduce the Gaverage value in that section. The previous Gavg value was 23/s at 10.5cm spacing between baffles. The G value was adjusted to 15/s and the corresponding spacing was 15cm. This change resulted in a noticeable visual change in floc size. Previously flocs were not growing in size in the final section of the floccualtor. After the change flocs started growing in the final section. After more observation of floc size almost doubling in the turn through the final port hole, the last baffle of the final section was removed to reduce G even further to see if the floc size increased noticed though the port hole could be achieved in the flocculator sections. After changing to final baffle spacing to 30cm flocs which lowered the Gavg value for that section to 4/s.
After all of these changes were made the large floc formation seen through the port hole and in the empty third flocculator section were witnessed in the final section of the flocculator.

Testing Set-up Modifications

Unknown macro: {float}

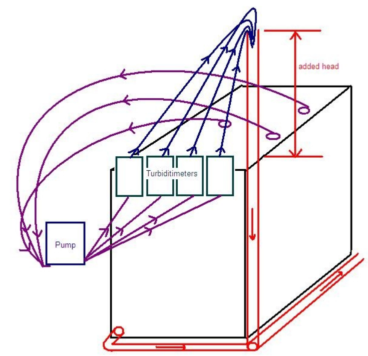


Schematic of the proposed Suspension System to hold tube settlers under water but still allowing it to collect at an angle of 60 degrees.

When the temperatures dropped this winter the sampling set-up started to have problems reporting viable results. One hypothesis was that the half submerged tube settlers, acting as sedimentation tanks, were not settling as well because of temperature change between the submerged portion and the portion at room temperature. It is believed that the water was flowing faster at the edges of the tubes than in the center, and because of this the residence time in the tube was made shorter. This issue was corrected by submerging the entire settling tube. A suspension system (#Submerged Settling Tube) was created to submerge the tubes and still keep it hanging at the correct angle. The schematic designed for this can be seen below. After implementing this set-up on one of the setting tubes in the tank it found that the upper baffle spacer got in the way of the string holding the lower end of the tube at the correct angle. Thus the set-up was altered to so that the tube was placed, still at 60 degrees and submerged, but instead of being suspended the bottom was supported by one of the lower baffle spacers and the top rested against the side of the tank. This was the same method of tube settler placement that was done previously just further down in the tank.

The temperature difference between the air temperature at the plant and the water temperature (close to freezing) is causing air to bubble out of solution in the turbiditimeters and it is believed that this might be causing false readings. The air doesn't stay in solution because the water is less soluble. To correct this problem the plan is to raise the pressure on this system (#new schematic) to a point that will keep the air in solution. The configuration of how water is drawn from the settling tubes to the turbiditimeters and then discarded was rearranged. Water flows from the tubes, through the pump then into the meters. From the meters the water travels up and drops into an exit tube about a meter above the tank. The outlet tube was extended as close to the ceiling as possible, this height ended up being about 8 feet above the top of the tank.

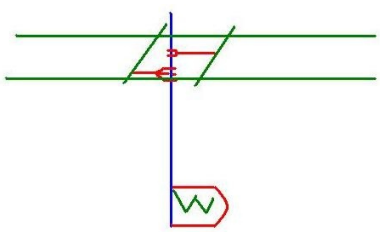
Unknown macro: {float}



Set-up to pressurize the system to keep air in solution.

The final modification that was made in the tank was to add a submersible light to the third section. This florescent light was added to allow us to be able to see flocs in the water. The light was attached to a pole and then suspended a few feet below the surface of the water. This light was held in place by two ring stand clamps attached to the light pole and to two separate bracing poles that rested across the section dividers.

Unknown macro: {float}



Set-up for the submerged light.

Tube Flocculator to determine ideal Gtheta values and a Gtheta, floc settling velocity relationship

A tube flocculator was constructed at the pilot plant in the Summer of 2008. It was constructed to determine what G and Gtheta values seemed to give optimal flocculation for raw water. This tube flocculator is identical to the tube flocculator being operated in the lab but it was running raw water and alum instead of kaolin clay, tap water and alum. The flocculator was divided into 10 sections of ten diffent Gtheta values. G through the tube is based on flow rate and at a flow rate 4.5 mL/s the Gavg value of the tube was about 35/s. A minimum G of 33/s was found in lab to be necessary to keep floc suspended.
This flocculator will also be connected to a clear settling column that will be used to determine settling velocities of the flocs from the tube flocculator. The purpose of this test was to determine the relationship between upward flow settling velocites and flocculator Gtheta values. It is being considered that with raw water flocculation that as the flocs get larger (greater Gtheta) they get less dense and there may be a point where large flocs have lower settling velocity that smaller denser flocs.

Results

It is important to understand the high flexibility of the facility for characterizing the optimal values of G and Gθ. As mentioned earlier, the highlight of this design is to provide the ability to model Honduran treatment plants and to improve flocculation performance. Through manipulation of G and Gθ, this set-up allows a systematic method to identify an optimal combination of the two parameters and verify their roles in efficient turbidity removal.
Initially, the plant would be operating at a constant G of 45 s-1 (controlled by Q). Easy relocation of sampling ports makes turbidity measurements possible at any point in the tank; and because of this arrangement, more refined turbidity vs. Gθ trends can be dictated along the flow path for any particular G value applied. Performance is measured by effluent turbidity; and the current goal is set at 1 NTU.

Results from testing of Uniform Spacing

A flow rate of 114 L/min was the closest flow rate to the target flow rate of 120 L/min that could be achieved. The residence time of the tube settlers was found to be 7.6 min, and the residence time of the flocculator was 18 min. In order to ensure that our measurement of the residence time of the flocculator was correct a test was run. This test consisted of turning off the alum and waiting till there was little or no floc formation. Then the alum was turned on and when there was observable floc it was timed to see how long it took to reach the end of the flocculator. When this measurement was done it was discovered that the residence time of the flocculator was about 35 min. This value was the value that was used in Process Controller. This and other evidence discussed in Data collection and troubleshooting below helped us to conclude that that was short circuiting of water in the flocculator. This evidence was used to make further adjustments to the tank, also discussed in detail in Data collection and troubleshooting.
At the beginning of the summer there were some minor adjustments made to the flocculator. The first is that the baffles at the end of the first section appeared to be rising up and away from the bottom of the flocculator causing baffle skipping. There was also some concern that water might be flowing under the dividers from the first section to the third section. To fix both these problems sand was added to the bottom of the flocculator at a thickness of about 5 cm.
The module in the last section of the flocculator also seemed to be drifting towards the end of the section. This was due to the force acting on the baffles causing them to drift with the flow. The force is due to the water level on either side of the baffle being slightly different due to head loss. This causes the pressure on one side of the baffle to be slightly higher at each point on the baffle than on the other side creating a force over the entire area of the baffle. The pressure on each baffle is translated through the PVC connector pipes from one baffle to another, until the last baffle and the final connector pipes are carrying the entire force. A MathCAD file labeled "Force on baffles" was created to assist with this calculation. Equations for head loss were used to find the head loss over just one section. It was found that there should be a head loss of 3.8 cm over each section. With this information, equations listed below were used to find the total force on each section and then the force each connector pipe would have to support.

$$P = \rho g h_l$$

$$A_{baffle} = L_s * w$$

$$F = P A_{baffle}$$

$$F_{pipe} = \frac{F}{N_{pipes}}$$

$$F_{pipe} = \frac{\rho * g * h_l * L_s * w}{N_{pipes}}$$

Variables:

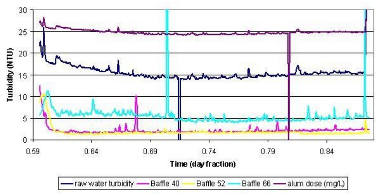
- Pressure (P): 372 Pa
- Density of water (ρ): 998 kg/m ^3
- Head loss (hl): 3.8 cm
- Baffle length (L_s): 72 cm
- Width of section (w): 30.5 cm
- Baffle area (Abaffle): 2,168 cm ^2
- Force (F): 80.7 N
- Force on each PVC pipe (Fpipe): 20.2 N
- Number of Pipes (Npipes): 4

With a head loss of 3.8 cm (which is the calculated head loss for each section of the flocculator) the force on the end connector pipes would be close to 81 N or around 20 N per connector pipe. This is a considerable forward force on the baffles and is the reason that the end connector pipes from the tank to the last baffle are instrumental in holding the baffles at the correct spacing from the end of the wall.
In the third section of the flocculator, the end connector pipes were cut to 6.7 cm which was causing the last baffle to push up against the exit pipe and deform the baffle as well as the flow area. The connector pipes that were cut at the end were not long enough to push against the walls of the flocculator. Measurements were taken and new connector pipes were cut and added on. The connector pipes are an important part of the design of the baffles because they transmit the force. If the pilot plant flocculator was not in three sections but in one long module like the design in Honduras the calculated force would be 242 N with each connector pipe supporting more than 60 N.
Another modification was a change in the exit pipe height. The calculations that were done in spring calculated the water height at the exit being 76.2 cm high. When first installed the pipe was cut to this height. However, there was an exit hole cut into the side of the flocculator and then an elbow installed where a pipe could be attached. This means that even with the pipe installed in the elbow it was already about 12.7 cm above the bottom of the flocculator. Therefore the pipe was re-cut to 63.5 cm to ensure a water level of 76.2 cm. However, even after the pipe was cut and installed the water level is about 81.3 cm. Future studies should again try to re-cut the pipe and maintain the water level at 76.2 cm.

Data Analysis

The graph below displays the graphed data that was obtained in the original configuration shown in Figure 9. Throughout the experiment the raw water turbidity remains around 15 NTU (dark blue). The alum dose is consistently around 25 mg/L because of the use of the log function of the turbidity which is relatively constant. The tube settlers after Baffle 40 (pink) and Baffle 52 (yellow) under these conditions consistently read settled water at about 2 NTU. This is markedly different from the tube settler after Baffle 66 (light blue) which is reading settled water turbidity at around 5 NTU or above. More tests were run and it was subsequently verified that water sampled from the third section was constantly at a higher turbidity. It was hypothesized that flocs were being broken up somewhere between the end of the second section and the beginning of the third section of the flocculator.

Unknown macro: {float}



Graph of Turbidity Results when one tube settler was placed at the end of each section.

Observation of the flow through the flocculator verified that there was good floc at the end of the first and second sections of the flocculator. However, when looking at the beginning of the third section the floc was smaller.

At the same time that the problem at the end of the flocculator occurred a problem with the tube settlers was discovered. After a certain period of time the tube settlers would become clogged. The flocs would get pulled up into the tube settler but instead of settling out and falling out the bottom they would start to stick to the sides of the tube settler. Eventually they would start to stick together as well and create a large mass of flocs. Part of these masses would be pulled up into the tubing and into the turbidimeters where they would clog the turbidimeter and skew the readings. When looking in the flocculator it appeared that we were creating very large flocs, and so the fact that they weren't settling out was confusing. As it turns out we were overdosing the flocculator with alum, and creating the chemical flocs of close to neutral buoyancy. After we lowered the alum dose the tube settlers no longer became clogged. The value of A was lowered to 7 mg/L and flocs were still being formed in the flocculator but the large masses of flocs were no longer seen in the tube settlers. Lowering the alum dose fixed the clogging problem and didn't appear to be detrimental to producing lower turbidity water. The water being pulled from the tube settlers was approximately 2 NTU. Since this didn't meet our goal of under 1 NTU the value of A was upped to 10 and kept at this value for subsequent data collection.

After the tube settler problem was corrected, data collection resumed. There still appeared to be floc breakup from the end of the second section to the beginning of the third. With closer inspection of the flocculator it was discovered that the third section had more eddy currents around the pipes and appeared to be at a higher velocity than the other two sections. It was eventually discovered that water from the first section was short circuiting the first and second sections of the flocculator by flowing from the end of the first section into the end of the third section. The flocculator was drained and the edges of the dividers that met the wall were caulked. Data collection again resumed and there didn't appear to be any flow from the end of the first section to the outlet.

After the flocculator was started again, the problem with flocs being broken up in the third section was given more attention. It appeared that the third section was flowing at a greater velocity than the first two sections of the flocculator. The first two sections had large flocs that were moving at a slower velocity while the third section appeared to have smaller flocs that were moving much faster. There also appeared to be more eddy currents around the PVC pipe connectors than in the other two sections.

At this time the head loss for the tank was around 2 cm, which was far short of the 11 cm of calculated head loss. G was found to be 16.5 s-1 with a Gθ of 1200. Then the head loss equation with the measured head loss was used to calculate minor loss coefficient. This was done because K is an empirical constant found through experimentation. The value of K that corresponds to the measured head loss with our given parameters was 0.558. This value is drastically different from the published and widely accepted value of 3.

With the vast difference in calculated versus measured head loss and the visual appearance of the change in velocity from the second section to the third section it was thought that the water might be somehow short circuiting the first and second sections of the tank to the third section. This would explain the greater velocity of the third section because it would be receiving more water than the other two sections. It would also explain why the head loss was so low. If the water was short circuiting the first and second sections of the tank then it would not be going through the flow path that was calculated and thus not experiencing as much friction, yielding a lower head loss reading.

The tank was again drained and water was poured between the edge of the dividers and the tank. When this was done it was discovered that there were leaks through the caulk that was applied. The space between the divider and the flocculator in some locations was substantial and the water had forced its way through. In some locations the gap between the edge of the divider and the flocculator were as big as a centimeter. It was clear that simply caulking the edges would not be a suitable solution. Kwik Foam was chosen to fill the gaps as it will conform to the space it is placed in and is a water sealant.

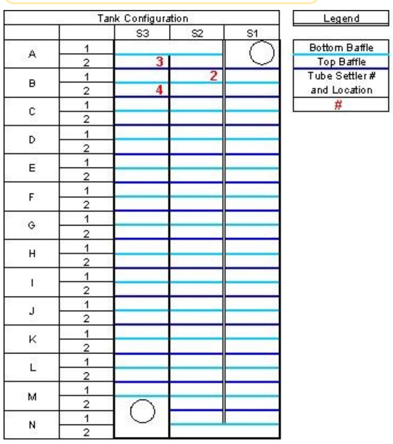
Both sides were filled with Kwik Foam from top to bottom. This was done by inserting a tube connected to the spray bottle inserting it in the space and slowly pulling it up while filling. The Kwik Foam worked very well in the gap between the beginning of the first and third sections. However, when the same method was applied to the gap at the end of the sections there was a bend in the plastic that caused the bottom of the divider to expand out and farther away from the edge of the tank. This created a bow shape if viewed from the side. This bow shape caused the port hole between sections 1 and 2 to close up significantly. The sides were re-caulked to provide an extra seal. This now allowed the caulk a spot to bind where before there had been large gaps. Calculations using the equation for the #Port Holewere done and a new width was chosen based on the area the port hole should be and the current length. This new width was measured out taking bowing into consideration and the port hole re-cut. The new width was found to be 5.8 cm.

With a wider port hole the bowing problem was fixed but now the width of the hole was larger than the spacing between the end of the flocculator and the last bottom baffle in the flocculator. This means that the last baffle at the end of the first section and the first baffle at the beginning of the third section would be short circuited. One option was to attach longer connector pipes to the end of the last baffle to increase the space between the flocculator and the last baffle. However, the method that was chosen was just to take a top and bottom baffle out. This option was chosen because with the rapid mix inlet pipe hanging over the edge of the flocculator installing and removing the first module of baffles was complicated. When trying to lower the module in it would need to be lowered at an angle which would stress the structure and break the connection in the middle of the modules. Removing two baffles resolved both issues. The connector pipes after the last baffle were elongated and the module was now smaller and easier to fit into place.

Removing two baffles in the first section resolved two problems, but the same problem was occurring in the second section. This time instead of removing baffles, which would decrease the overall Gθ of the flocculator, the structure of the first two baffles was altered. The bottom baffle was angled, so that on one side of the baffle the spacing between it and the next baffle was smaller. In order to preserve the area of the space and not increase G the opposite was elongated. Now the flow area instead of being a rectangle was a trapezoid. From looking at the area it appeared that by shrinking the connector between the first bottom and top baffle in the second section that the skipping would no longer occur. This along with the formula for the area of a trapezoid rearranged was used to calculate the length of the other connectors to ensure that the area and G remained the same.

After the major adjustments to the flocculator were made experiments were focused on the end of the second section and beginning of the third. This was done to ensure that the sealing of the dividers to the side of the tank had fixed the short circuiting problem. There appeared to be more flow through the first and second section sections and there was no discernable difference in velocity between the three sections. Tests were run to see if the floc breakup was less. Visually this appeared to be the case, and tests were run to see if the settled turbidity at this point was lower. The next set-up that was tried clustered the turbidity meters around the second port hole. This was done in an attempt to determine if flocs were breaking up around that port hole. A schematic of this set-up can be seen below.

Unknown macro: {float}



Schematic of tube settler placement used to determine if flocs were breaking up moving into the third section.

A graph of the turbidity data for this configuration can be seen below.

Unknown macro: {float}

[!Pilot Plant^graph turbidity data set-up 2.JPG|width=200px!|Pilot Plant^graph turbidity data set-up 2.JPG]

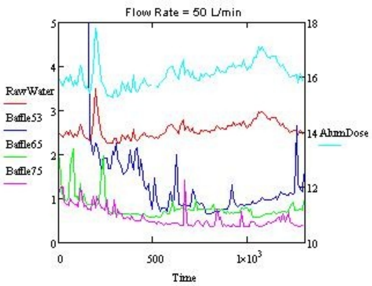
Graph of turbidity data for tube settler placement around the second port hole.

The flow rate was lowered to 50 L/min and the three tube settlers were spaced out in the last section of the flocculator. They were positioned this way because if it was the tank then there should still be floc breakup in that section, however if it was due to Gθ then the water being sampled should be gradually decreasing in turbidity. The tube settler represented in blue is at the beginning of the third section, the tube settler in the middle of the third section is in green and the final tube settler at the end is in pink. Therefore if the third section is producing floc there should a drop in turbidimeter from the blue line to the green line and then to the pink. Figure 19 is a graph of the performance of the third section under a flow rate of 144 L/min and is a graph of the performance under a flow rate of 50 L/min.

It appears that with a flow rate of 50 L/min (talk about what G and Gθ that is) the third section of the tank is creating flocs and not breaking them up. As you can see in Figure 21 there is a drop in turbidity from the floc turbidity 4 to floc turbidity 2. This is

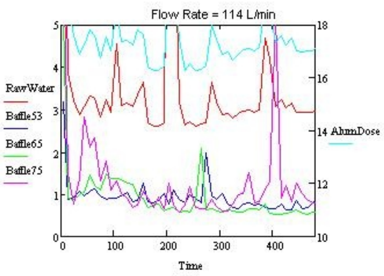
not as clear with a flow rate of 114 L/min. This trend was seen on multiple other days when testing with the flow rate of 114 L/min was done. With this information it is assumed that floc breakup is occurring due to over mixing and not to problems with the design of the flocculator. It appears that the intensity of mixing in the third section was too great for the flocs that had been formed, suggesting that G is too large.
Graphs of the turbidity data collected from the third section for contrasting flow rates of 50 and 114 mL/min can be seen below. It appears that with a flow rate of 50 L/min (talk about what G and Gθ that is) the third section of the tank is creating flocs and not breaking them up. With this information it is assumed that floc breakup is occurring due to over mixing and not to problems with the design of the flocculator. It appears that the intensity of mixing in the third section was too great for the flocs that had been formed, suggesting that G is too large.

Unknown macro: {float}



Graph of turbidity data for tube settler placement in the third section at 50mL/min. This was done to determine in the tank itself was breaking up flocs or if it was the Gθ value.

Unknown macro: {float}



Graph of turbidity data for tube settler placement in the third section at 114mL/min. This was done to contrast the test done previously at 50mL/min.

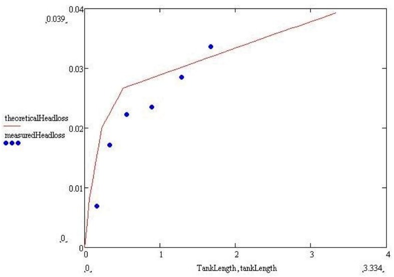
Head Loss

After the short circuiting of the sections was discovered and the flocculator repaired, the head loss readings increased to 4 cm. This value of head loss yields a G of around 23 s-1 and a Gθ of close to 17,000. The head loss was not near the calculated value of 11 cm and on close inspection of the tank it could be seen that the divider bowing was causing compression of baffles in the third section and was allowing skipping in parts of the first and second sections. In an attempt to correct this problem two 2x4 pieces of wood were clamped to the edge of the dividers along their length. This helped a bit with the bowing. Also string was used to pull the divider near the third section closer to the second section. After this change was made the head loss increased to 7 cm which gives a G of 30 s-1 and a Gθ of 22,600. With this head loss if the coefficient of K is back calculated using equation 19.
When this calculation is done the value of K is 2, which is close to the published value of 3. Measurements of each section were taken. The first section had a head loss of 1.5 cm, the second a head loss of 3.5 cm and the third a head loss of 2 cm. The middle section shows that a head loss of 3.5 cm can be reached if the dividers are correctly spaced and the baffles made to fit correctly. When this value is used to back calculated K a value of 2.94, which is essentially 3, is found. This supports the accepted value of 3 being used in calculations for head loss, and suggests that skipping is occurring if the measured and calculated values of head loss are not close. Upon visual inspection the first section does appear to have space between the baffles and the divider still. If the dividers could be made to stay flush against the first section it would ensure skipping would be less of a problem and that the baffle design is not problematic with water skipping around the edges if they are cut to fit snug in the spacing. G for section 1, 2, and 3 was calculated and found to be 25 s-1, 38 s-1, and 29 s-1.

Preliminary Results from Testing of Tapered Spacing

Overall data was collected from two flocculator set-ups. We tested the original set-up where there where 79 baffles spaced equally throughout the flocculator at 6.4 cm apart. And then we switched the flocculator set-up and collected more data for a tapered flocculation set-up that consisted of 39 baffles. The purpose of these experiments was to test whether or not our assumption that better and more efficient flocculation could be achieved with a tapered baffle configuration was accurate.
A head loss analysis was done on the tapered set-up to determine if the theoretical parameters being used were accurately describing the system. The collected head loss data was found by comparing water height in a free surface tube to the water height in the tank. A hole was drilled between the third and fourth baffles a tube was inserted into a quik-connect fitting attached there. This tube was open to the atmosphere at the other end and the water height in this tube is a direct measure of head loss through the plant when compared to water levels at other points. The graph seen below compared the theoretical head loss for the tapered set-up with data that was collected from the first section of the tapered set-up. Data was not collected from the section because method used for collecting the data in the first section could not be repeated in the second section. The graph of our measured headloss versus the theoretical head loss can be seen below.

Unknown macro: {float}



Graph of comparison between theoretical and measured head loss.

Based off of looking at the graph it seems that at least for the first three sections we are over calculating the amount of head loss that the system is creating.
Further analysis will include changing the theoretical parameters such as K to try and get the theory curve to match the data curve. This analysis should give us a better representation of what K is for the AguaClara plants.

Conclusions from the Testing of the Uniform Flocculation Configuration

After the initial design and construction of the flocculator was complete, attention focused on getting the flocculator running. The beginning of the summer was spent ensuring that all the individual parts of the flocculator and tube settler setup were working and that all Process Controller methods were setup. Once this was finished data collection started and it was at this time that flaws in the design became apparent. Attention then shifted to fixing those flaws. The design of the dividers was the most problematic portion of the tank. The dividers were made as a separate piece and then lowered into the tank. This created several spaces and large gaps between the tank and the divider where water could skip sections and head directly towards the outlet. Several steps were made to fill the gaps and stop the leaking caused by the gaps. This caused more problems as the dividers were not straight and easily deformed, which caused bowing and other deformations when the Kwik Foam was used. The divider design thus caused skipping around the end of sections as well as around baffles. The leaks in the tank were discovered through observation, and head loss measurements. The first leak was discovered by observation of the tank and the subsequent leaks discovered and fixed through use of the head loss tubes and sampling in the tank.

Alum Dose

For the majority of testing, alum dose was set by equation 18. After the change of A from 15 to 10 was made this approach was effective for the low turbidities that the flocculator experienced this summer. Hopefully in the future the raw water turbidity will change enabling testing of higher turbidities. Through use of equation 18, observing the floc tank and conversations with the operators at the water treatment plant it has become apparent that there is still a lot of research that needs to be done regarding alum dose. Observing the floc tank was helpful in being able to identify different kinds of floc and what different alum doses looked like in the water entering the water treatment plant. The water treatment plant has now switched to a different coagulant but if they had to go back to alum they said they would use past experience and alum doses as well as jar tests to set their doses. This suggests that for each water treatment plant an equation, formula or at least a rule of thumb could be developed off of past water treatment for future dosing. If this formula would be translatable to other water treatment plants and different water types is uncertain. The run increment alum dose test should help to shed light on alum dosing as it allows the alum dose to be changed while at a relatively constant raw water turbidity. Hopefully the data from this test will show either an optimum dose or a small range of optimal doses for specific settled water turbidity.

Design Suggestions (for future plants)

If a serpentine flow is again used, future designs should include a way to make the dividers a more central part of the design, and a material that does not deform easily but holds its structure and can be sealed to the tank should be chosen. If this is not a possibility then re-enforcement to the dividers should be added to ensure that deformation does not cause problems with baffle skipping. This way the width of the sections can be easily controlled as well as locations where leaks could be problematic could be observed during installation. The problem with making the divider and the tank not one central piece is that it is difficult to make the two pieces fit together and make them water tight.

Another suggestion that would make maintenance of the tank easier would be to include an outlet that could be opened and closed nearer to the bottom of the tank than the outlet pipe currently is. The current design leaves water at a height of a few inches above the bottom that needs to be pumped out before the tank is fully drained. Even then with the design of the dividers the bottom of the tank can never be fully drained because the bottom piece of the divider covers most of the bottom of the tank. This is problematic if repairs to the caulk or Kwik Foam need to be made, as they seal best on dry surfaces.

When dealing inside the tank the current configuration of the modules is sturdy and provides a structure that allows the baffles to move as a whole maintaining baffle spacing. This is an advantage as it ensures that they are evenly spaced and that the value of G is constant throughout each module. One of the problems encountered this summer was that in the pilot plant configuration the inlet and outlet are both pipes that were added that decreased the space in the first and last section of the flocculator. If this design is to be replicated the space that the inlet and outlet occupy should be taken into account when designing the number of baffles. This is due to the fact that the connector pipes that are used to keep the baffles from drifting to the end could become caught on the exit pipe and cause the baffles to be pushed against the inlet. When lowering the modules into the tank they need to be lowered very carefully and each portion of the section needs to be lowered at the same time, necessitating at least two people, usually three. If the modules were bent the connector pipes would pop out of the caps and it would be hard to replace them. The connectors are important because of the forces that they carry.

Experiment Suggestions

It is assumed that all leaks due to dividers have been fixed either with sand, or with Kwik Foam and caulk. This idea is supported by the increase in head loss and the visual appearance of the velocity in all three sections being equal. The major concern that should be further evaluated is skipping around the edge of the baffles due to divider bowing. After skipping is either confirmed to be minimal or fixed future experiments should include focusing on the third section. Data collected and analyzed up to this point suggests that the third section is breaking floc up. In building this pilot plant it was hoped to test tapered flocculation where changing the value of G over the three sections is explored. It is suggested that future experiments change the spacing of the third section from a G of 29 s^{-1} to a G of 15 s^{-1}. In order to ensure that the design for G does not actually yield a lower value of G than wanted it is suggested that the head loss for the third section is measured and the K value back calculated. This new K value should take into account any skipping that is occurring around the side of the baffles. It is assumed that the skipping in this section is coming from between the baffles and the divider. Thus when G is decreased only the baffle spacing and thus number of baffles will be changed. This new K value assumes that the skipping is occurring uniformly over each baffle and thus should account for the skipping around the baffles that will be left. It should yield a more accurate calculation of head loss and G as it takes into account the space between the dividers and the baffles, which should stay constant as the same baffles will be used, just less of them. When this is done the focus should be on collecting data on the effect of settled water turbidity and floc formation. It is hypothesized that a lower G will not break up larger flocs but still provide gentle mixing allowing smaller particles to be integrated into floc.

Developing Turbidity Profiles along the Flocculator

This testing procedure has two parts: finding the optimal alum dose on the day of testing and running the Profile Test. This procedure was developed and implemented in the Spring '08 semester.

Optimal Alum Dose Testing

Because the pilot plant takes water directly from the stream, environmental conditions change all the time and affect the incoming turbidity to the plant as well as the chemical composition of the particles causing turbidity. It is therefore necessary to determine the best alum dose for each day of testing to ensure the formation of good flocs. This requirement was implemented in the following way:

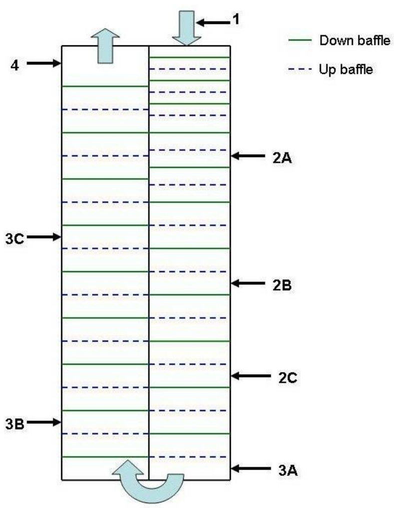
The Process Controller was used under the "Increment Alum" setting, which starts the Alum Dose at 0 mg/L, and increments at 5 mg/L until it reaches a maximum of 40 mg/L. Each of the alum doses ran for a 30-minute period, or for about 3 times the residence time of the tank. After the completion of the test, data processing was performed to select the data from the last 10 minutes of each individual alum increment. The first 20 minutes of data were rejected because the residence time in the flocculator was 10 minutes, and the residence time in the tube settler was also about 10 minutes. Therefore, in order to get readings from the final turbidimeter that were representative of the alum dose that we were testing, we discarded the first 20 minutes of data at each alum dose. The outgoing turbidity (from turbidimeter 4) was then analyzed for each increment, and the alum dose achieving the lowest turbidity was selected for the second part of the experiment.

Profile Test Procedure

Unknown macro: {float}

Picture of the Flocculator set-up.

Unknown macro: {float}



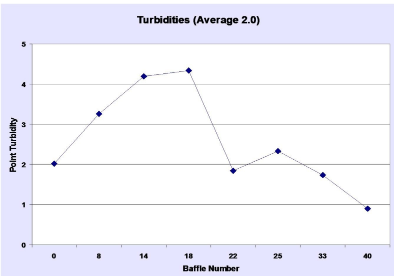
Experimental Set-up of the Tube Settler Placement.

The purpose of this experiment was to develop a profile of flocculation at different places along the flocculator. In order to do this, we moved the tube settlers to different points along the length of the flocculator and tested the turbidities of the water after it passed through the tube settler and reached the turbidimeter. In Experimental Set-up of the Tube Settler Placement above, you can see a schematic of the experimental set-up. A photograph of the same set-up is also shown. The experiment has three parts, A, B, and C, each lasting for 45 minutes. During the experiment, the location of tube settlers 2 and 3 were moved to different places along the flocculator as shown above. Turbidimeter 1 was always testing the incoming water, and turbidimeter 4 was always testing the turbidity of the water at the end of the flocculator (location 4 above). Along with moving tube settlers 2 and 3, we emptied tube settler 4 of water between parts A, B, and C of the experiment. This is because when the tube settler is filling with water, plug-flow conditions exist in which velocity gradients cannot develop, and flow up the tube settler is more even. So, by emptying tube settler 4 of water, we ensured that the potential effects of this condition in the tube settler were even across all the tube settlers.
Likewise, when performing the data analysis after the experiment, we found an increase in the turbidity to unreasonably high levels (on the order of 100 NTU) for about 10 minutes after moving the tube settlers. This was because the air in the tube settlers which was being pumped through the turbidimeters. Therefore, only the data at the end of each part of the experiment was used (approximately after 10 minutes of running). The removal of the air can be easily observed in the data when the system appears to have reached a steady-state.

Results from Profile Testing of Tapered Flocculator Set-up Spring '08

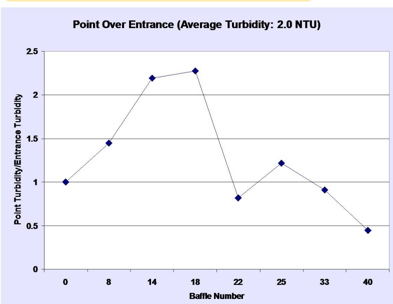
- Move this section to a new page since this wiki page is getting too long and slow.
- Consider using the wiki option for directly creating graphs in the wiki. Your graphs have a relatively small amount of data so it would be easy to do. See the wiki style guide for an example graph.
- Put more than one plot per graph to make it easier to compare results.
- add links to your page from the Pilot Plant page.

Unknown macro: {float}



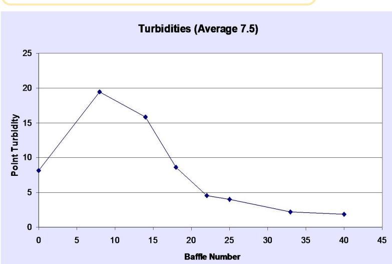
Turbidity Profile with Average Incoming Turbidity at 2 NTU.

Unknown macro: {float}



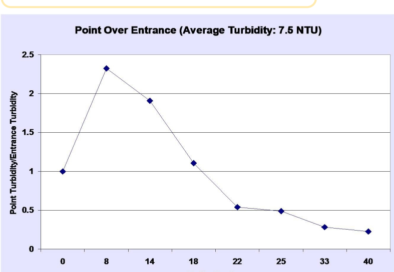
Turbidity Profile Ratio with Average Incoming Turbidity at 2 NTU.

Unknown macro: {float}



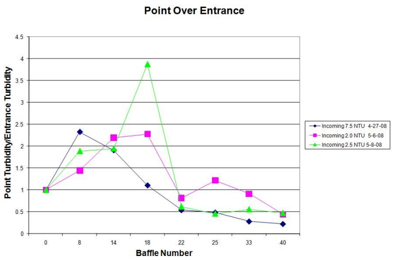
Turbidity Profile with Average Incoming Turbidity at 7.5 NTU.

Unknown macro: {float}



Turbidity Profile Ratio with Average Incoming Turbidity at 7.5 NTU.

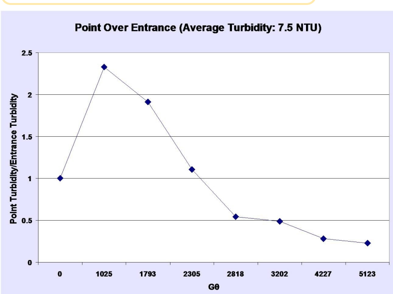
Unknown macro: {float}



Combined Turbidity Profiles from Three Experiments.

In figure the Combined Turbidity Profiles from Three Experiments graph, it can be seen that a general trend exists in which the turbidities taken from the end of the tube settlers first spike at the beginning of the flocculator to about 2 times what they were in the incoming water. Then, they take a rapid dive to a fraction of the original turbidity. The most likely reason for this is the formation of flocs which are not large enough to settle in the tube settlers at the beginning of the flocculator but are large enough to greatly increase the deflecton of light in the turbidity meters. Later in the flocculator, larger flocs form, and these have a settling velocity of greater than 10 m/day. Therefore, they settle in the tube settlers and do not add to the turbidity in the turbidimeters.
It appears that a trend also exists towards the peak turbidity happening earlier in the flocculator when incoming turbidity was high, and later in the flocculator when turbidity was lower. This result suggests that the flocculator is more effective when turbidities are higher. This is consistent with the expectation that the collision rate is proportional to the floc volume fraction, φ_{floc}. However, the settled water turbidity from the end of the flocculator was lower when incoming water was lower. The outgoing turbidity was 0.9 NTU, 1.3 NTU, and 1.8 NTU for the trials where the incoming turbidity was 2.0, 2.5, and 7.5 NTU, respectively. It is important to examine the absolute turbidity at the outgoing points because this is the parameter that determines the effectiveness of chlorine and overall safety of the water produced by our system. We need to achieve water that is consistently safe to drink because the reliability of our water treatment plants affects the health of our beneficiaries on a daily basis.

Unknown macro: {float}



Turbidity Profile vs. Gθ.

The graph above shows the flocculation profile versus Gθ as calculated with the model developed by Leslie Campbell of the Design Team. This model is as follows:

Unable to render {include} The included page could not be found.

Where totbaffle is the number of baffles before the testing plant, Qplant is the flow rate of 100 L/min, and FlocTankwidth was the width of the flocculator sections, or 12 inches. The other parameters were set as follows: Π_{cell} = 2, kb =3, and the viscosity of water was 1 * 10 ^-6 m ^2/s.

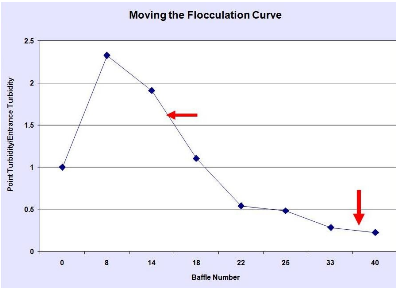
By examining this graph, we can see that the total Gθ of this set-up was about 5000, which similar to the Gθ of the flocculator at Ojojona, which is about 4000.

Results from Hydraulic Flocculator after Altering the Baffle Spacing in the Final Section

Not only was there a visible increase in floc size that was noticed in final section of the flocculator but the tube settler gathering water from the end of the flocculator began reporting a drop in the turbidity values. The meter started consistently reporting values less than 1 NTU.

Future Work:

Unknown macro: {float}



Future Turbidity Profile Goals.

In the future, the new team would want to achieve flocculation profiles that have the peak turbidity happen earlier in the flocculator, and most importantly, an end turbidity that is consistently below 1 NTU across different environmental conditions. The following suggestions are aimed towards achieving that goal.

1. Continue to develop flocculation profiles. We suggest that new team members develop at least 2 profiles using the current set-up, so that they learn how to run the procedure and the data analysis. Then, they can use this tool on different set-ups. Hints for accomplishing this:

- In order to get the tube settlers to stay at a 60 degree angle, rest the bottom end along supporting tube on one wall of the flocculator and the top end along the other side of the flocculator. This achieves approximately 60 degree angle. To keep the tube settler in place (remember, after you move them, they are filled with air, tend to float), tuck the sampling line between a baffle and the wall. This is an effective way of securing the tube settlers.

1. A common problem that occurs is that the lines from the sampling point to the turbidimeters fill with sediment and the pump is unable to get water through them. If this happens, you should remove the clogged line, including all connections, and clean them. As this is a common problem, you may want to clean the lines before starting an experiment to increase your chances of a successful experiment.

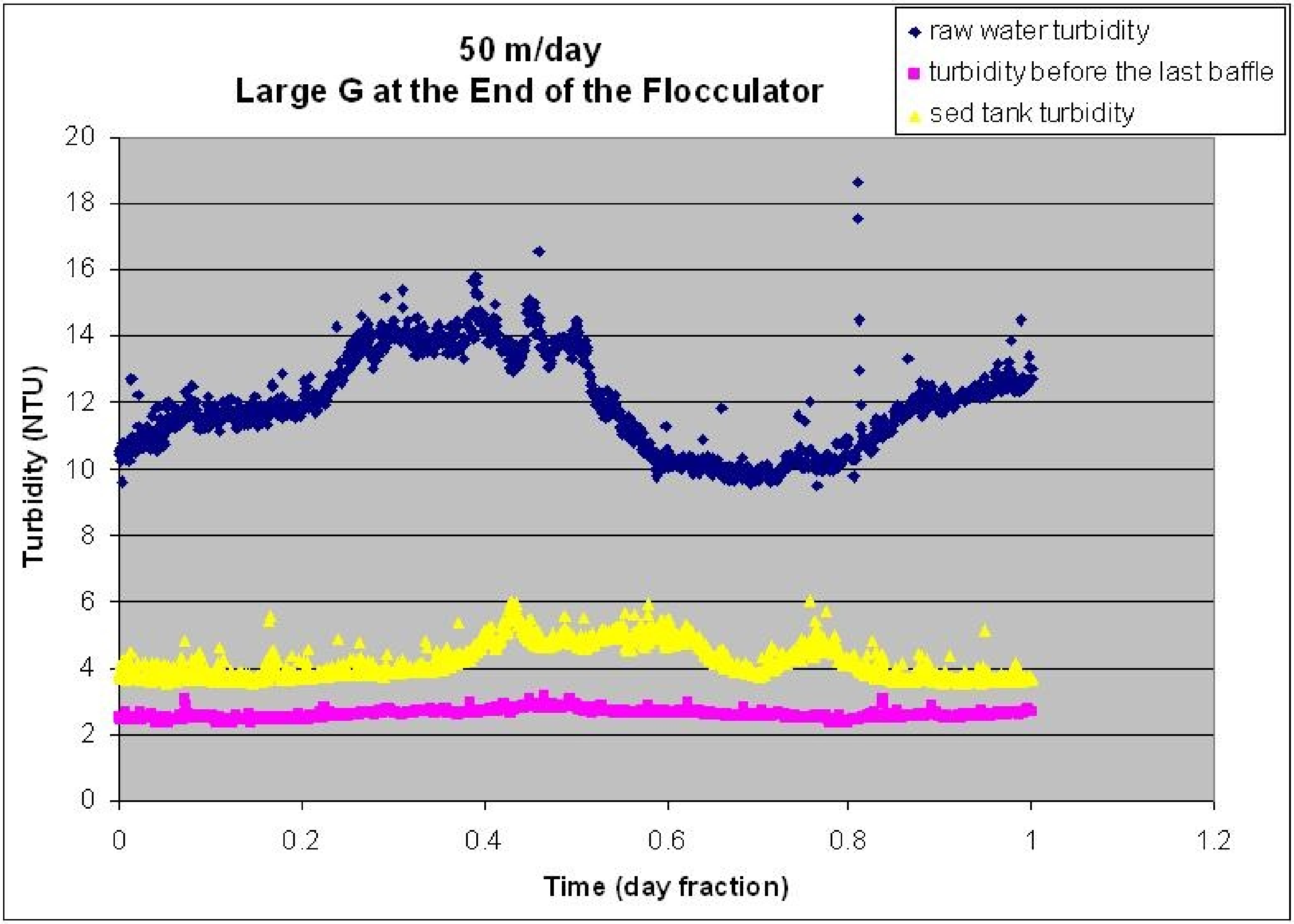
1. Adding Obstacles - Create a set-up that includes obstacles between the baffles. Obstacles might be pipes place perpendicular to the flow. See the "In-line Obstacles" section under "The Theory of Tapered Flocculation" section above. The idea behind this modification would be to make the velocity gradients more even throughout the sections. Previous AguaClara research has indicated that velocity gradients were much higher around the turns than along the length of the baffles. More efficient flocculation would be possible if average gradients were closer to maximum gradients. With this set-up, run the same data analysis tests. (You may find that you can't put obstacles in the baffle space where the tube settler is.) Get at least 3 sets of data and compare the shape(s) of the flocculation profile curve between these tests and the tests performed without obstacles.

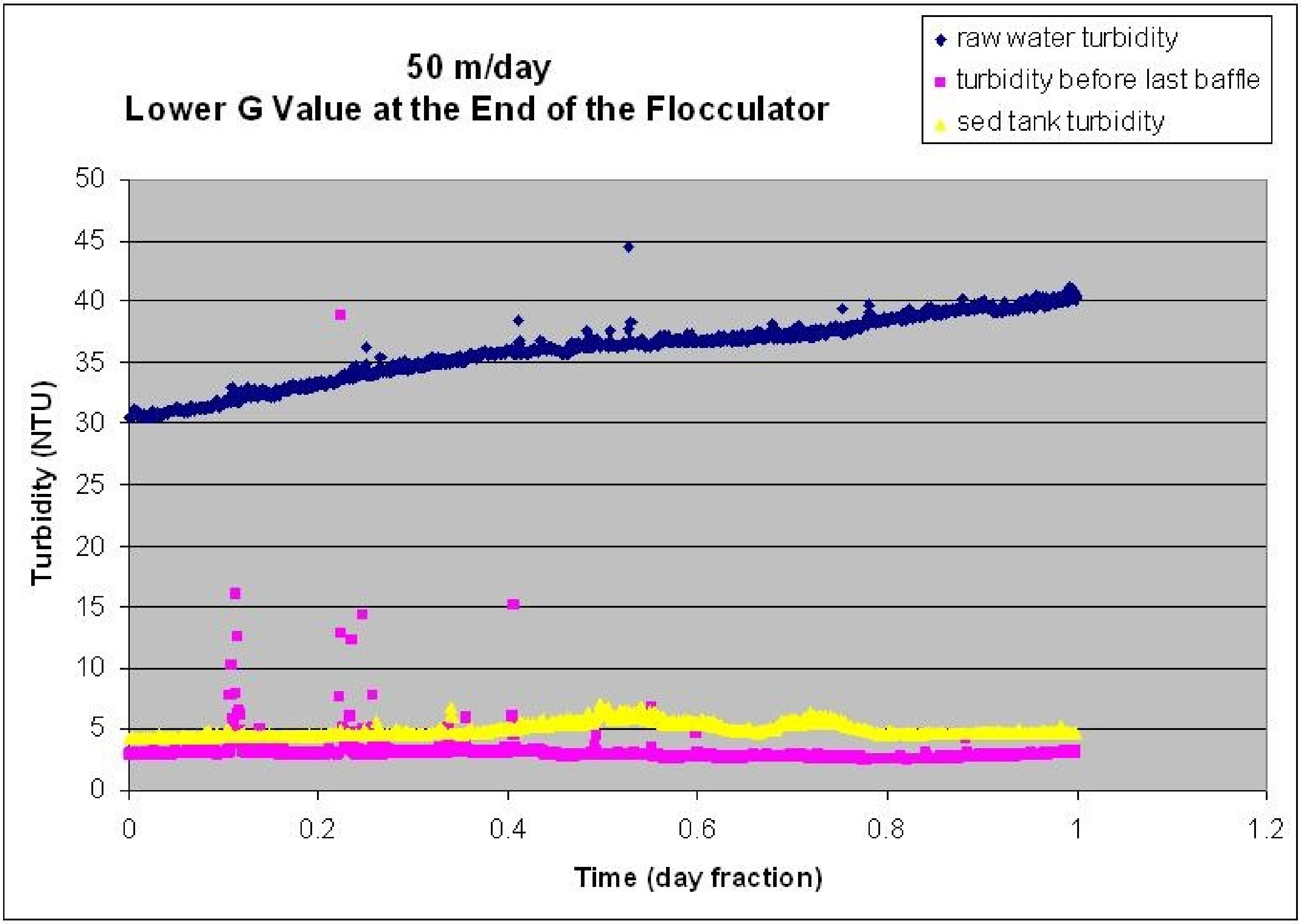
1. Change the baffle spacing in the first part of the flocculator and observe the impact on the turbidity profile. The pilot plant flocculator was developed under the assumption that all flocs have about the same density. However, research from by the AguaClara team suggests that smaller flocs in the beginning of the flocculator are more dense than larger flocs that develop later in the flocculator. This would mean that the flocs at the beginning of the flocculator can handle higher sheer values than expected, while the flocs at the end of the flocculate need lower sheer values than expected. To test this hypothesis, the new team should change the construction of the baffles in the flocculator, adding more closely spaced baffles in the beginning, and developing a flocculation profile for that set-up. They could also make the spacing at the end of the flocculator larger, and develop a flocculation profile for that set-up.

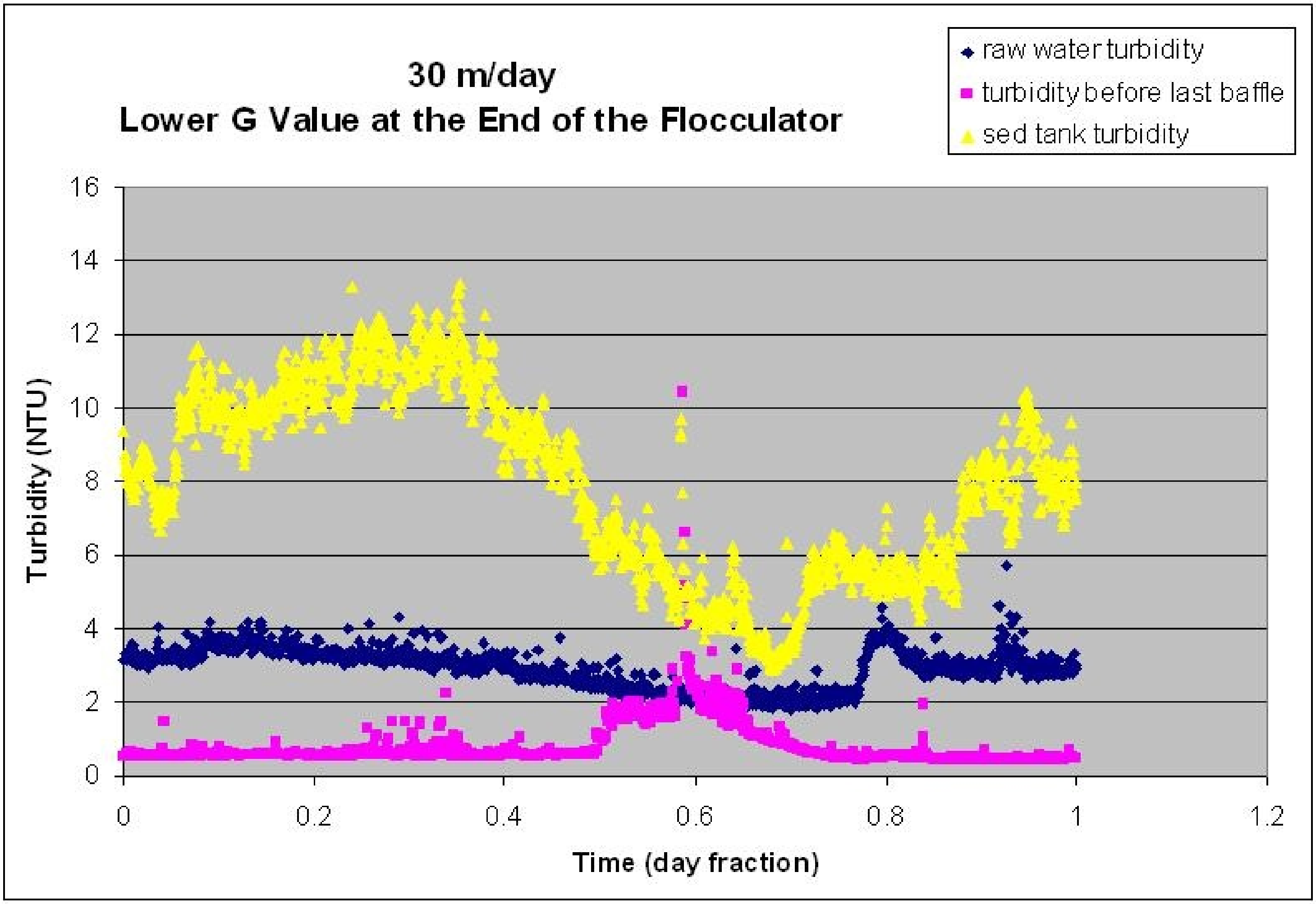
1. Although the big drop in turbidity seems to happen after 20 baffles, there continues to be improvement all the way to the end of the flocculator. This suggests that the flocculator isn't long enough yet. It is possible that the flocculator doesn't have a high enough $G\theta$ and that $G\theta$ is limiting the water quality. It is important to investigate this as soon as possible (early this summer) since it might be the secret to getting 1 NTU water!

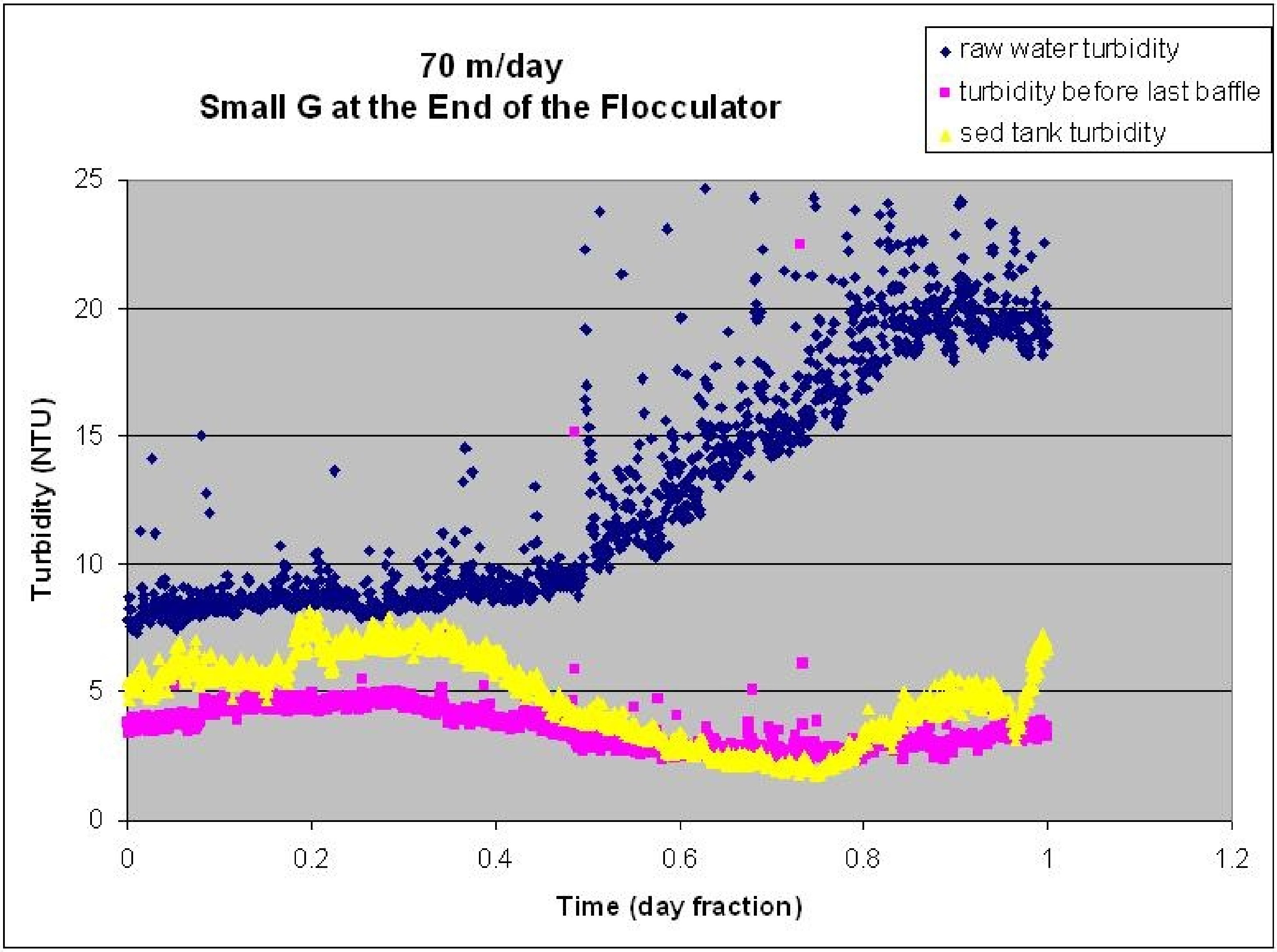
Results From Velocity Tests

The first four graphs are velocity tests from the old sedimentation tank.

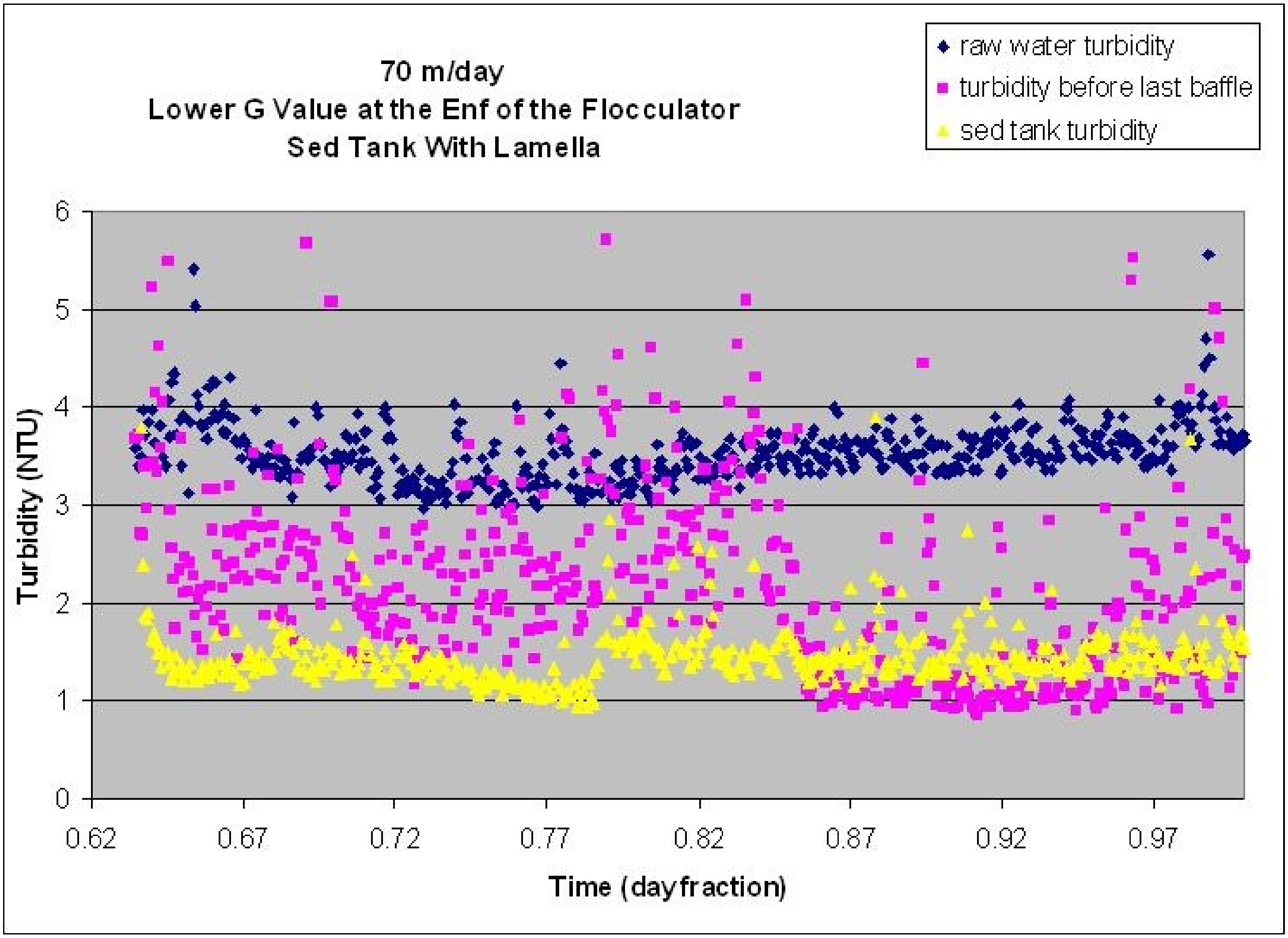

50 m/day
Large G at the End of the Flocculator
raw water turbidity
turbidity before the last baffle
sed tank turbidity
Turbidity (NTU)
Time (day fraction)
0
2
4
6
8
10
12
14
16
18
20
0.2
0.4
0.6
0.8
1
1.2


50 m/day
Lower G Value at the End of the Flocculator
raw water turbidity
turbidity before last baffle
sed tank turbidity
Turbidity (NTU)
0
5
10
15
20
25
30
35
40
45
50
Time (day fraction)
0
0.2
0.4
0.6
0.8
1
1.2


30 m/day
Lower G Value at the End of the Flocculator
raw water turbidity
turbidity before last baffle
sed tank turbidity
Turbidity (NTU)
0
2
4
6
8
10
12
14
16
0
0.2
0.4
0.6
0.8
1
1.2
Time (day fraction)



This graph is from the new sedimentation tank, with the lamella in place



results from velocity tests

If you have a disability and are having trouble accessing information on this website or need materials in an alternate format, contact web-accessibility@cornell.edu for assistance. www.cornell.edu/privacy-notice.cfm