Contact Chamber, Fall 2017

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Abstract

The introduction of coagulant into turbid water causes collisions of suspended solids particles with coagulant nanoparticles, which promotes the growth of flocs. However, a large portion of the coagulant dose adheres to pipe walls rather than influent particles, requiring a higher than necessary coagulant dose to account for this effect. In order to minimize coagulant wastage, an apparatus called the contact chamber was fabricated to increase collisions between influent particles and coagulant. The Fall 2017 Contact Chamber team analyzed the performance of the contact chamber by comparing influent and effluent turbidity in experiments with and without a contact chamber. After several trials, it was concluded that the contact chamber did not improve the effluent turbidity. In fact, the effluent turbidity with the contact chamber was significantly greater than the effluent turbidity without the contact chamber.

Introduction

Coagulation in drinking water treatment poses many difficulties in optimization of the coagulant dosage. As the coagulant and clay-water stream is introduced into the contact chamber, a fraction of the coagulant is inevitably lost to the walls of the chamber thus wasting coagulant that was intended to be mixed with the influent stream to promote floc growth. The utilization of contact chambers and coagulation offered an additional step in removing suspended particles from a drinking water influent stream. The difficulties posed by suspended solids in the drinking water were derived primarily in their characteristic variance. Suspended particles can vary in electrostatic profiles, shape, size, and densities. Since these suspended particles in water tend to share the same surface negative charge, the particles repel each other when one suspended solid particle is too close in proximity to another suspended particle. Proper dosage of coagulant into the waste stream was effective in increasing collision frequency between coagulant, clay, and suspended solids in order for them to be extracted from the waste stream.

In previous semesters, the contact chamber teams in AguaClara have assessed the efficacy of the addition of a contact chamber before flocculation in order to promote greater collision frequency between the coagulant nanoparticles and the suspended solids. This method increased residence times and promoted thorough mixing of the coagulant so that there is a uniform level of treatment in the chamber (Akpan et al., 2017).

The focus of the Contact Chamber team of Fall 2017 was to assess the drinking water treatment value of a contact chamber within the treatment system. The first stage of the experiment included a preliminary data collection series in which the performance of the water treatment without a contact chamber was compared to that of a system containing a contact chamber. In this preliminary assessment, the team established a baseline of turbidity of the influent stream, and then assessed the performance of effluent stream when coagulant and clay were introduced into the stream. Following the analysis of the performance of the system without the contact chamber, and then the contact chamber was brought into the system to quantify the performance. The team's initial hypothesis was that the contact chamber would allow for more intensive mixing process as the influent eddies increase turbulent flow, recirculating possibly unmixed portions of the waste stream. Further analysis was required in order to gain a concrete and quantified understanding of the mechanics behind a contact chamber. This fortified the team's opinion on whether or not the implementation of a contact chamber proved to be worthy of integration into the AguaClara system. Alternatively, the coagulant, clay, and raw water stream could simply be introduced directly into the flocculator in lieu of a contact chamber. In the water treatment industry, there has been a long-standing gap in documented research outlining the mechanics behind a contact chamber and its value in drinking water treatment Demirel and Aral (2016b). The research of this current contact chamber team has broken down the process in a piecewise fashion to reach a holistic understanding of the intricacies behind the mechanics of contact chamber operations.

Literature Review

Coagulation is a physiochemical process that is applied before the filtration process to aid in the removal of solid particles from water. Coagulants work by destabilizing the charge present on dispersed solids particles. Stable particles of clay and organic substances found in influent raw water are negatively charged, causing particles to repel each other and remain suspended in solution. As positively charged coagulant is added to the water, the negative charges are neutralized, allowing the particles to adhere together into aggregations called “microflocs”. The rapid mix chamber quickly disperses the coagulant throughout the clay-water mixture. Following a rapid mixing time of approximately 1 to 3 minutes, the clay-water mixture is then mixed slowly, beginning the flocculation process. Additional particle collisions allow the coagulant to form interactions with inorganic polymers, increasing the size of microflocs to larger floc sizes (Zoupanos and Zouboulis, 2008).

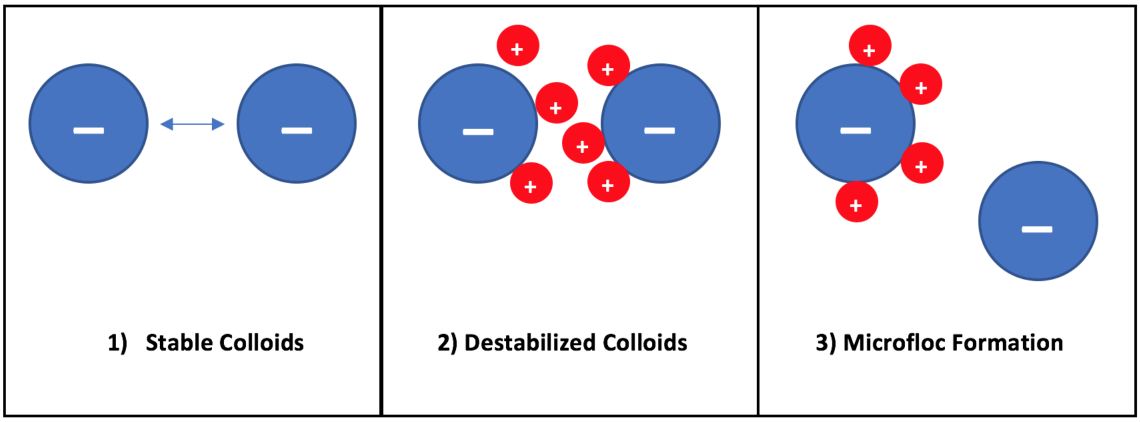


Figure 1: 1) Originally, the negatively charged solids particles repel each other. 2) As positively-charged coagulant is added to the mixture, they adhere to the negatively charged colloids, neutralizing the charge and destabilizing the particles. 3) With the removal of charge, the destabilized colloids can now adhere to each other, forming microflocs (Mazille, 2012)

In North America, the most common coagulants used to treat drinking water are aluminum or iron salts; Al2[SO4]3 (alum), in particular, is most widely used. Alum and water react by hydrolysis to form several monomeric and polymeric species. AguaClara plants use a commercially available polymeric aluminum coagulant called polyaluminum chloride (PACl). Polymeric species are advantageous because they tend to form flocs faster than alum and are less sensitive to changes in pH, allowing the coagulant to perform well even in colder water (Exall et al., 2000). The faster rate of flocculation is due to the higher charge PACl carries, which makes it immediately ready for coagulation, as opposed to alum, which first must react and form coagulant in situ (Matsui et al., 1996).

In a study of coagulation kinetics, batch experiments were conducted to examine the different ways that PACl and alum destabilize particles and the different factors that affect how quickly particles are destabilized. Since previous research showed that the rate of collisions between particles is slower than the rate of particle destabilization, particle destabilization is the rate-determining step. Therefore, the efficiency of the coagulation process depends on the rate of particle destabilization, and as a result, optimizing the particle destabilization rate would have the greatest impact on coagulant efficacy (Matsui et al., 1996).

Two methods were used to assess the movement of particles as they aggregate into flocs. The first method measured the turbidity fluctuation. As the turbidity fluctuated about the mean value, fluctuations indicated the different states of aggregation. A double wavelength light was used to indicate the size of flocs. In the second method, the particle counting method, the counter detects decreases in light intensity caused by single particles passing through the cell, counting each particle as it passes by. Using this information, the number of particles within the flowing suspension can be calculated for each floc size. The results of this experiment supported the hypothesis that particle destabilization rates vary with particle concentration. As the number of particles increases, the probability of collisions increases, which promotes coagulation (Matsui et al., 1996).

In addition, the study analyzed the effects of mixing intensity, pOH, and water temperature on coagulant properties. Increased mixing intensity also increased the number of coagulant-particle interactions, creating larger flocs. The study found that coagulant is less effective in colder water, due to increases in viscosity, changes in equilibrium constants, and slower rates of the hydrolysis and precipitation reactions key to coagulation. In addition, the seasonal fluctuations in influent particulate matter associated with changes water temperature may also have an effect on coagulant efficiency. Decreases in temperature also affected the hydroxide concentration; the optimum pOH range was identified to be less than 7.3 for alum and PACl (Matsui et al., 1996)

The topic of interest that the Fall 2017 Contact Chamber team addressed was determining whether or not the use of a contact chamber would aid in more effective collision rates with coagulant particles adsorbing to an influx of clay particles. In doing so, the team hypothesized to have calculable differences between choosing to implement a contact chamber or not. In order to evaluate the efficiency of the use of this system, the analysis will likely consist of initial, qualitative observations were made as the coagulant dispersed with clay particles. The team will do so by taking note of the residence times within the contact chamber, which the preliminary model will be a clear tube so that a contrasting dye can be applied to see how the recirculated zones within the contact chamber coagulate until the dye has reached a fully-mixed state. It has been determined through flow and tracer transport methods that vorticity field is the key parameter to use to discern areas of jet flow and recirculation zones within the contact chamber. The vorticity gradient and the flexion product shed the most mathematical insights on the topic of differentiating recirculation and jet zones, as well as fluid to fluid flow separations. From this, the team will have a mathematical analysis of the validity behind the qualitative results. The ratio of t90/t10, or the Morrill index, describes the travel time of 10% and 90% of the cumulative normalized tracer concentration observed at the outlet of the contact chamber, and is commonly used to characterize the mixing efficiency of a contact chamber. The basis with which the indices were characterized was classified as a "black box" analysis since the mechanisms of mixing within the contact chamber were overlooked or not analyzed (Demirel and Aral, 2016b). The objective of this experimental analysis of behavior of the conservative tracer in the contact chamber is to note the mixing of the chemical within recirculation zones where the tracer is briefly retained before release, as well as the interactions between the jet zones and recirculation zones. Identifying these interactions were important because they both played a role in the aggregate mixing process. The difficulties posed in this analysis were the monitoring methods utilized in literature. The index bases were derived by measurements made only at specific outlet points throughout the system. There was no data highlighting the mechanics of mixing within the contact chamber itself.

In an effort to maximize the efficiency of the rate of contact in between suspended solids particles and nanoclusters within the chamber, it was experimentally proven to be effective to modify the hydraulic designs of a series of baffles ("guiding walls") in order to minimize events of recirculation within the chamber (Demirel and Aral, 2016a). Preventing recirculation puts more emphasis on the ability of nanoclusters to cling to the suspended solids particles instead of being lost to the walls of the chamber, which will decrease treatment efficiency potential for a given dosage of coagulant.

Previous Work

The Contact Chamber subteam was created in Spring 2016 to find a way to decrease the amount of "free coagulant," defined as the portion of coagulant that does not adhere to the influent particles. Free coagulant is an issue because as the coagulant adheres to the walls of the contact chamber rather than the influent particles, a higher dose of coagulant is required to create floc particles that will be settled out. By optimizing the contact chamber so that the amount of coagulant that adheres to the influent particles is maximized, the subteam can reduce the coagulant dose required for flocculation, and therefore reduce plant operation costs.

The first Contact Chamber subteam of Spring 2016 tested the effects of coagulant adhering to the flocculator walls using a mass balance approach and determined a logarithmic relationship between coagulant deposition and influent turbidity. The Fall 2016 subteam used a different approach to measure coagulant efficacy, by relating head loss with coagulant buildup. The team measured the changes in tube diameter due to coagulant adhering to the walls of the flocculator (Figure 2).

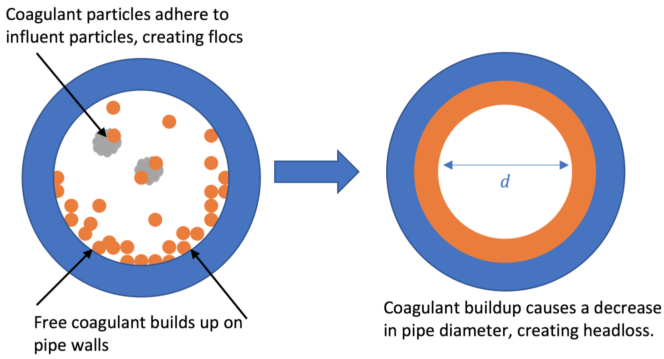


Figure 2: Coagulant that does not bind to influent particles instead adheres to pipe walls. The buildup of coagulant then leads to a decrease in pipe diameter, causing an increase in head loss.

The team conducted experiments by running only coagulant and water through the flocculator to measure the effects of coagulant alone. Several tests were conducted with varying flow rates, allowing the team to determine the threshold flow rate for coagulant build up. The team then analyzed the effects of adding clay to the water, in order to simulate the effects of influent particles through the flocculator. Different turbidities were tested to determine how effectively accumulated coagulant was removed from the flocculator walls. The results showed an immediate drop in headloss once clay was added to the flocculator. The team also studied the effects of adding a contact chamber to the flocculation process, placing it between the point of coagulant dose injection and the flocculator. The team hypothesized that the chamber would reduce free coagulant, and as a result, decrease coagulant loss. The results showed no definitive advantage in using a contact chamber; however, the team concluded that this was because the clay turbidity (5 and 50 NTU) and flow rate (0.6 mL/s) used for the experiment did not allow coagulant buildup in the first place (Akpan et al., 2017) The Spring 2017 subteam repeated the same experiment, running more trials and applying numerical analysis to the results. The team analyzed coagulant loss by using changes in head loss. They continued to used the straight flocculator and contact chamber setup from the previous semester to replicate these experiments.

Three different experiment setups were used to test the effects of clay and turbid water with and without contact chambers. Experiments were run with turbidities of 5 NTU and 50 NTU, which represented the low and high turbidity conditions, respectively. The first experiment was run using only coagulant and water and tested how coagulant attachment to walls of flocculator affected head loss. As time increased, a higher quantity of coagulant attached to the walls, leading to higher head loss. The experiment showed an approximately logarithmic relationship between time and head loss (Akpan et al., 2017).

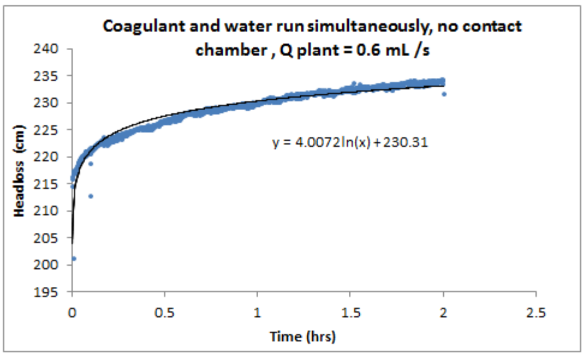


Figure 3: As experiment time increased, the head loss increased in a logarithmic relationship. The increase in head loss indicates coagulant buildup on the pipe walls. Figure from Spring 2017 Rapid Mix Contact Chamber report (Akpan et al., 2017)

In the second experiment, the team ran raw water through the flocculator for some time before coagulant pump was turned on. There was initial jump and fall in head loss as the pump was turned on and off. The cause of the initial jump was hypothesized to be due to the increased flow rate from pumping coagulant, which caused an instant increase in head loss. Another reason was that as coagulant reaches the entrance of the flocculator, some coagulant immediately attached to the walls, causing a minor head loss due to the decrease in pipe diameter. The drop in head loss stopped after coagulant injections were stopped, but did not return to original values at t=0, as they did in the experiments conducted the previous semester. The threshold flow rate for an effect on head loss was between 1.0 and 1.6 mL, as determined by the previous subteam, so later experiments were conducted between these flow rates. From this experiment, it was shown that clay does not significantly decrease head loss within the flocculator. For the Spring 2017 team, the headloss increased even after there was no coagulant running through system, due to increases in flow rate from the clay solution or clay sticking to coagulant already present on the walls.

The third experiment was conducted with the same flow rates for a turbidity of 50 NTU. The results show a similar constant increase in headloss before and after clay added. However, head loss increases were greater due to the higher flow rate, which suggests higher mass flow rate of coagulant through flocculator and faster rate of coagulant building up.

In addition, the Spring 2017 subteam designed a new contact chamber to increase the ratio of total clay to tube surface area. The goal of the design was to reduce head loss to 50 cm and residence time to 1 minute. In previous calculations, at 50 NTU, the ratio of the total clay particle surface area to the flocculator surface area was $5 * 10^{-3}$, and the contact chamber ratio was 0.172. The Spring 2017 subteam improved the design to minimize contact chamber surface area, reaching a clay to tube surface area ratio of 0.991 (Akpan et al., 2017). This surface area ratio favors coagulant adherence to influent particles rather than to the walls. In calculating the surface area ratio, the team modeled clay particles as spheres and the contact chamber as a cylinder (Akpan et al., 2017). The experimental results of the Spring 2017 team supported the hypothesis that using a contact chamber in the coagulation process decreases the head loss, and therefore reduces the amount of coagulant adhering to the pipe walls.

Methods

Experiment Setup

The experiments were run using a Proportional-Integral-Derivative (PID) controller. The PID controller, run by ProCoDA, automates the formulation of a clay stock solution by using a feedback response loop. After a desired target turbidity is set, the PID controller automatically adjusts the clay inflow by running the pumps until the turbidimeter read the desired turbidity. The values of P, i, and D were set to 0.5, 0.25, and 0, respectively. In the initial experiment, without a contact chamber, the influent turbidity was kept constant at 10 NTU, while the coagulant dose was adjusted to output an effluent turbidity of 2 NTU.

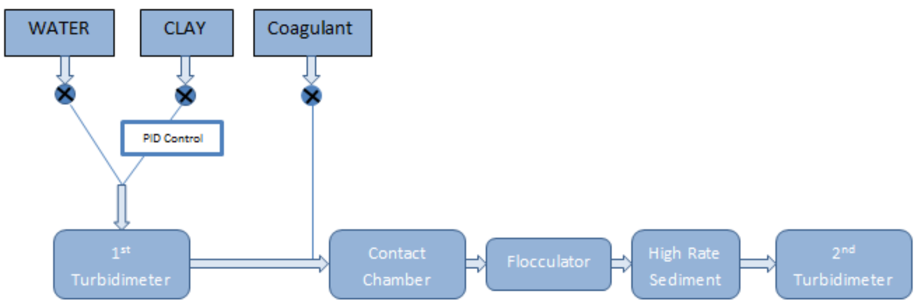


Figure 4: Schematic of experiment setup. The water pump was set to 114 RPM, and the coagulant pump was set to 15 RPM. The clay pump was run using the PID controller in ProCoDA.

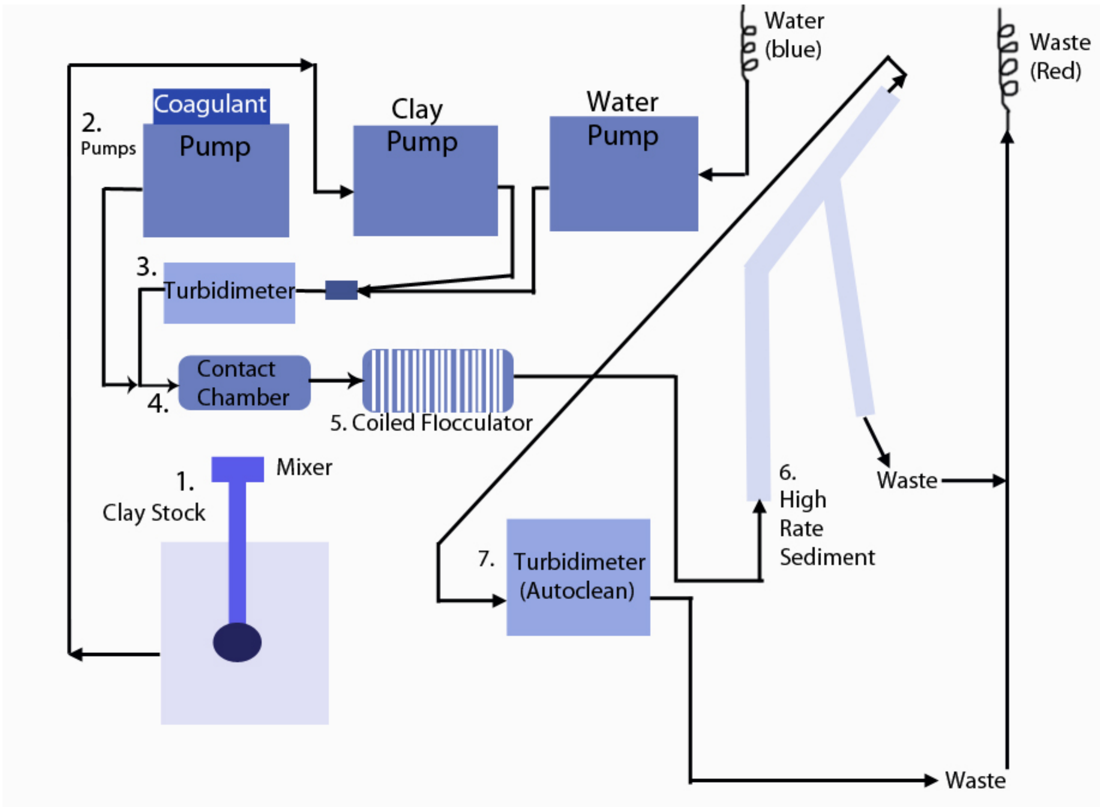


Figure 5: The experiment setup was identical to the those of other AguaClara subteams, which included High G Flocculator, High Rate Sedimentation, and all of the Dissolved Species Removal teams.

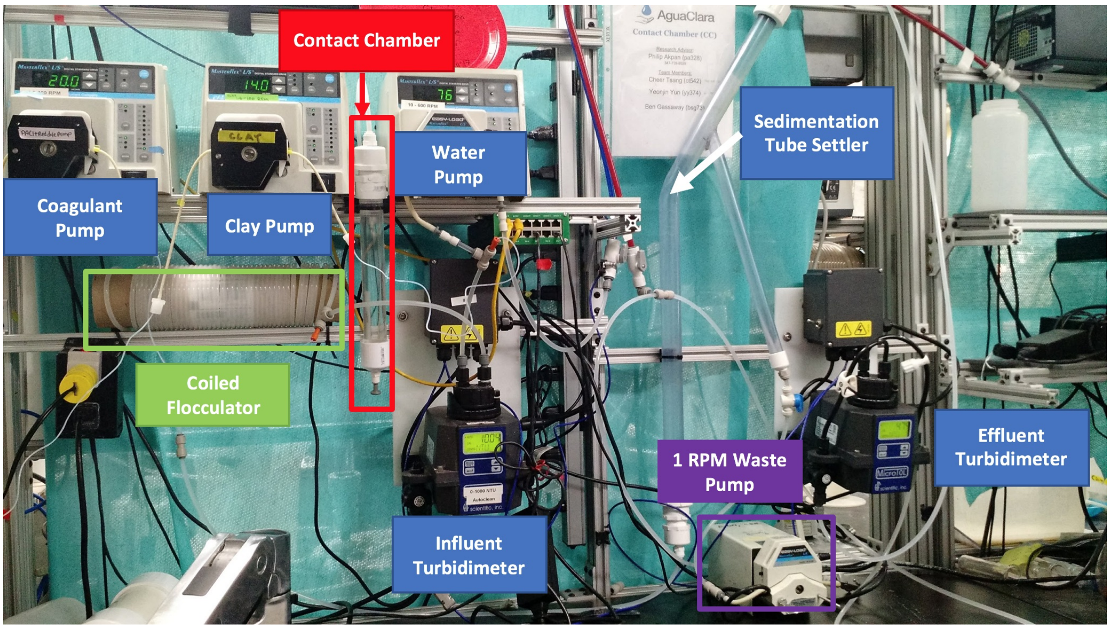


Figure 6: The completed experiment setup included the contact chamber, coiled flocculator, and sedimentation tube settler. The 1 RPM waste pump was added to control flow up the tube settler.

In the experimental setup (Figure 5, Figure 21):

1. The raw water line delivers water to the water pump. The clay stock is prepared and mixed.
2. The water and clay mixture is pumped to the turbidimeter.

3. The turbidimeter measures the influent turbidity of the clay and water mixture.
4. Clay, water, and coagulant are mixed in the contact chamber.
5. The coiled flocculator further mixes the coagulant and clay solution.
6. The solution then flows to the sedimentation tube, where flocs are settled.
7. The second turbidimeter measures the effluent turbidity.

Equipment

Pumps

1. Easy-load Masterflex 1 RPM Pump (Floc Weir Discharge)
2. (2) Materflex 1.6-600 RPM Pumps
   (a) Coagulant Pump
   (b) Clay Pump
3. Masterflex 10-600 RPM Pump (Raw Water)

Turbidimeters

1. HF Scientific Inc MicroTOL Turbidimeters 0-1000 NTU
   (a) Measures influent stream after introduction of clay into raw water stream before entering contact chamber
   (b) Measures effluent stream at the end of the plant following flow through sedimentation tube

Contact Chamber and Sedimentation Tube

1. Clear PVC tube
2. PVC pipe end caps

Tubing and Fittings

1. Hard tubing
2. Microbore tubing
3. Yellow-blue size soft tubing
4. Size 16 soft tubing

Containers

1. 5-liter Tank: Clay stock storage
2. 1-liter bottle: Coagulant Stock

Materials

1. Raw water
2. Distilled water
3. Kaolinite Clay
4. Coagulant PACl (70.9 g/L concentration)

Determining Clay Concentration

Initial tests were conducted using a setup which ran a specific concentration of clay through the turbidimeter to approximate a relationship between clay concentration and NTU. Estimations were made using data from the AguaClara summer 2007 research on Clay Concentration in Stock Solution for Desired Influent Turbidity (Figure 7).

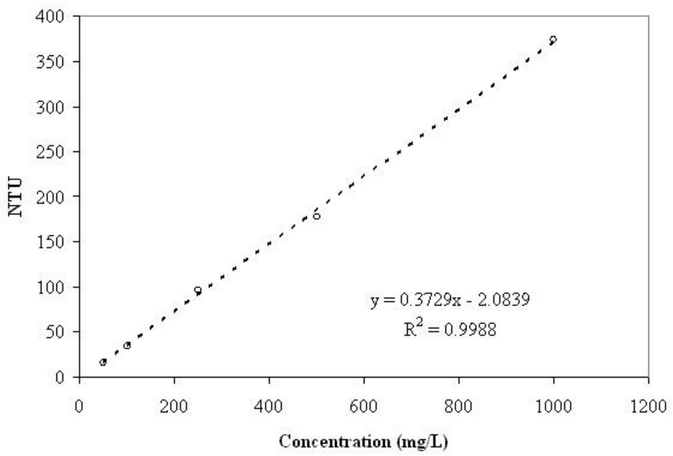


Figure 7: The relationship between the added clay concentration (mg/L) and the resulting turbidity (NTU) can be approximated by a linear trendline.

Using this linear relationship, in order to obtain the desired inflow turbidity of 10 NTU, a mixture of 32 mg/L clay concentration was prepared, resulting in a turbidity of approximately 23 NTU. The team ran three identical trials, mixing the clay-water mixture for 30 s and running the clay pump for 1 minute. In addition, in order to account for clay settling so that mixing times could be adjusted, the team ran an experiment to measure settling rate. The mixer was allowed to run for 30 s, and immediately after, the the clay pump was run for an extended period, allowing the clay to settle out of the mixture. The decreasing outflow turbidity was recorded, and a linear trend was observed 8.

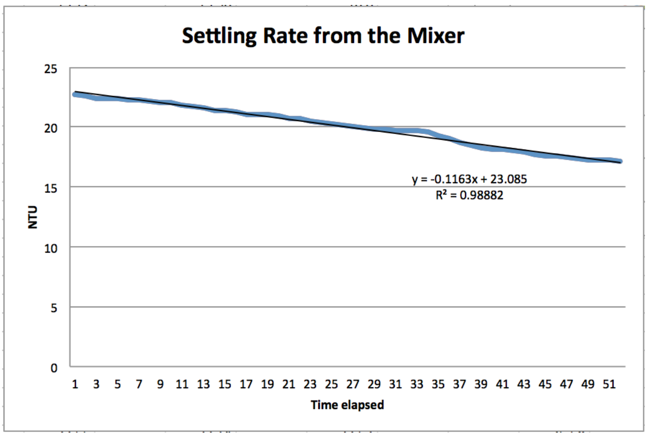


Figure 8: The settling rate of clay after mixing showed a linear trendline.

Subsequent experiments were run using PID, thus eliminating the need to experimentally determine initial clay concentration.

Experimental Apparatus

Design

The contact chamber was modified from the previous semester's design. The contact chamber has a diameter of 2.54 cm (1 in) and a length of 25.4 cm (10 in). The length of the contact chamber is ten times the diameter to model the length of the turbulent jet stream (Figure 9). Since the turbulent jet creates eddies that recirculate water at the outer edges of the jet stream, by minimizing the recirculation near pipe walls, the amount of coagulant that adheres to the walls can be reduced.

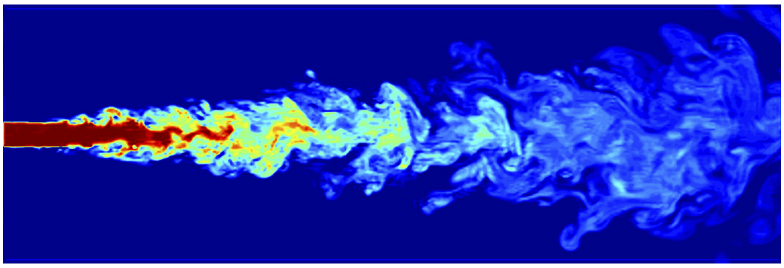


Figure 9: Image illustrating the turbulent jet stream. The turbulent jet creates eddies, which recirculates the water close to the pipe walls. Image from Lawrence Livermore National Laboratory (Lawrence Livermore National Security, 2017).

Fabrication

The redesigned contact chamber was fabricated using a 25.4 cm (10 in) clear polycarbonate pipe. PVC caps were attached on the ends of the pipe using PVC cement to waterproof the contact chamber. Threaded push-to-connect connections were attached to each end of the contact chamber to allow tubing to be attached.

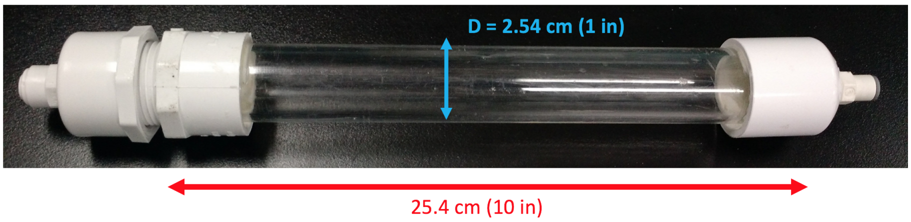


Figure 10: Redesigned contact chamber, with a length that is ten times the diameter.

Procedure

In order to reach a target influent turbidity of 10 NTU using PID control, a clay stock solution was prepared. The coagulant dose was adjusted by a manual user input to reach an effluent turbidity of approximately 2 NTU in initial experimentation. Additionally, calculations were made in order to determine the necessary pump speed for the raw water input into the system to satisfy the volumetric flow demands of the plant. Once a pump speed was confirmed, this pump rate was set by a manual input to the peristaltic pump.

Following the inputs of pump speed setpoints, all valves were set to their open positions (raw water feed, floc weir outlet, and the waste stream outlet). When all preliminary tasks stated above were completed, experimental trials were then able to be carried out. The PID set point was adjusted from the OFF state and into the PID Control state, which initiated the clay pump to feed the clay stock solution into the system. The remaining two pumps for the raw water feed and coagulant stock solutions were powered. The clay pump speed adjusted according to changes in the influent turbidimeter in order to maintain an average turbidity of 10 NTU over the course of the experimental trials.

Experiment Parameters

Several experiments were run, varying water pump speed, coagulant pump speed, clay concentration, and coagulant dosage, to achieve an effluent turbidity of 2 NTU (Table 1).

Table 1: Summary of experiment parameters, with pump speeds in RPM, clay stock concentration in g/L, and coagulant stock concentration in g PACl/L.

Experiment	Trial	Water Pump Speed	Coagulant Pump Speed	Clay Concentration	Coagulant Concentration
1	1	114	40	0.6	0.03545
	2	114	20	0.6	0.03545
	3	114	OFF	0.6	0.03545
2	1	114	20	0.6	0.2836
	2	114	15	0.6	0.2836
3	1	76	10	0.6	0.2836
	2	76	10	0.4	0.2836

- In Experiment 1, the coagulant pump speed was varied, and the coagulant stock concentration was set to 0.03545 g PACl/L.
- In Experiment 2, the coagulant pump speed was also varied, but the coagulant stock concentration was increased to 0.2836 g PACl/L.
- In Experiment 3, the coagulant stock concentration was kept at 0.2836 mg PACl/L, and the coagulant pump speed was kept constant at 10 rpm, but the clay concentration was varied.

Preparing Stock Solutions

1.) Clay

To prepare the clay solution, 5 liters of water was added to an 8 liter container. For Experiment 1 and 2 (Table 1), the concentration of clay was set to 3 grams per 5 liters of water. The reasoning behind this concentration was two-fold: i.) to allow for a low flow rate of clay solution through the system such that this volumetric flow would have negligible impacts on the overall flow rate of the the system, and ii.) to prevent sharp spikes in influent turbidity measurements. This prevented any dramatic compensation responses by PID. The clay concentration was lowered to 2 g/L in Experiment 3 due to the lower flow rate of water.

2.) Coagulant

In Experiment 1, 2.5 mL of 70.9 g/L concentration PACl was added to 5 L of distilled water. However, since this coagulant dose did not have an effect on effluent turbidity even at high coagulant pump speeds, the coagulant stock concentration was increased by eight-fold. In Experiments 2 and 3, to prepare the coagulant solution, 1 liter of distilled water was added to a 1 liter-capacity bottle. It was essential to use distilled water because the coagulant particles could more effectively adhere to clay particles in a deionized environment. In order to achieve a floc blanket at such a low flow rate throughout the system, 4 mL of 70.9 g/L concentration PACl were added to the volume of water. Under the constraints set by PID control, the coagulant dose was continually adjusted throughout the experiment in order to maintain an average influent turbidity of approximately 10 NTU.

Calculating Pump Speed

The water pump speed was initially calculated using a target upflow velocity of 3 mm/s in the sedimentation tube. However, since the AguaClara High Rate Sedimentation subteam reduced the upflow velocity to 2 mm/s, the water pump was recalculated. The flow rates of the coagulant and clay inflow were assumed to be negligible. Assuming laminar flow and neglecting friction, the continuity equation was used to calculate the flow rate through the pump:

$$Q = Au \quad (1)$$

where Q is the volumetric flow rate in m^3/s, A is the area of the sedimentation tube in m^2, and u is the upflow velocity in m/s. With a 1 in (2.54 cm) sedimentation tube diameter and an upflow velocity of 2 mm/s, the volumetric flow rate was calculated to be 1.01 mL/s.

In order to convert volumetric flow rate in mL/s to units of revolutions per minute (rpm), the "Auto Tutorial for Peristaltic Pumps" found on the AguaClara Confluence site was used. For size 16 tubing, the volumetric flow rate was estimated to be 0.8 mL/rev. Thus, the water pump speed was set to 76 rpm for an upflow velocity of 2 mm/s.

Statistical Analysis

Data analysis was performed using Microsoft Excel's Data Analysis ToolPak. Student's t-test Two-Sample Assuming Unequal Variances was used to compare effluent turbidity with and without the contact chamber (Figure 15). The Anova: Single Factor test was used to compare effluent turbidity with the contact chamber, without contact chamber, and with the contact chamber after cleaning out the turbidimeter. A p-value of less than 0.05 was established for significance.

Results

Establishing a Control

In the first experiment, the water pump speed was set to 114 rpm to achieve an upflow velocity in the sedimentation tube of 3 mm/s. The main purpose of this experiment was to determine an appropriate coagulant dose which would yield an effluent turbidity of 2 NTU, by varying the coagulant pump speed, which subsequently changed the mass flow rate of coagulant. It was observed that the sedimentation tube did not have enough floc particles to form a floc blanket; as a result, the team hypothesized that the lack of a floc blanket was causing the high effluent turbidity readings.

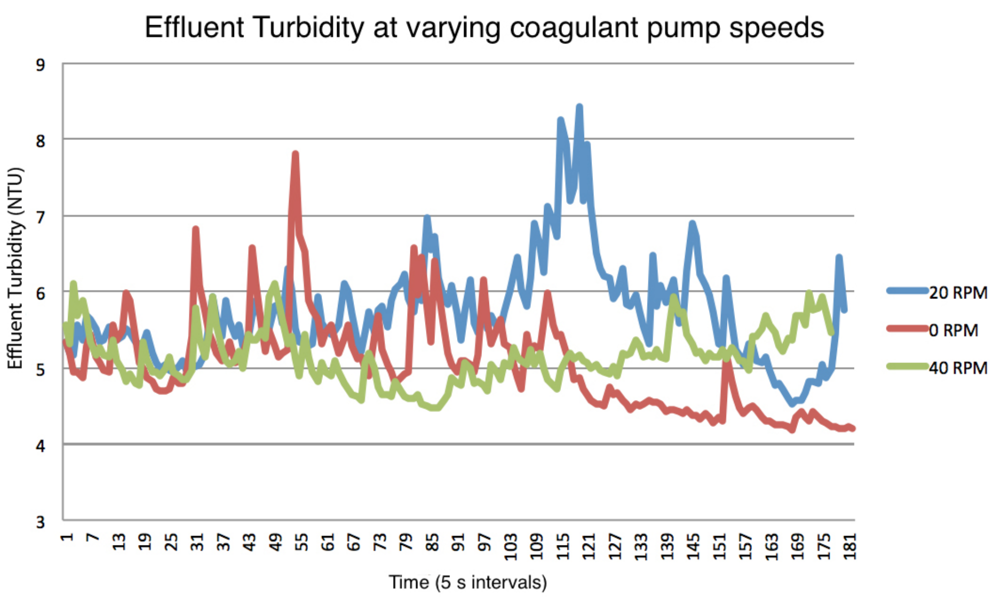


Figure 11: Change in effluent turbidity at intervals of 5 s with varying coagulant pump speeds. The coagulant stock concentration was kept constant at 0.03545 g/L, while the coagulant pump speed was varied from 0 rpm, 20 rpm, and 60 rpm.

There was no distinct difference between three different coagulant pump speeds (Figure 11). Furthermore, even with no coagulant running through the system (0 rpm), the effluent turbidity was similar to when the coagulant pump was running at 20 and 40 rpm, which meant that coagulant had no effect on the effluent turbidity at all. Since it was hypothesized that the lack of a floc blanket caused such a high effluent turbidity, the team decided to increase the coagulant dosage in order to form a floc blanket.

In the second series of experiments, the coagulant dosage was increased to be eight times more concentrated than in Experiment 1. The reason for increasing the concentration by eight-fold was that at a 4 times higher concentration, the results were essentially the same as Experiment 1. In Experiment 2, the largest observable change was that the floc blanket started to form in the sedimentation tube. After the formation of the floc blanket, the effluent turbidity was significantly reduced.

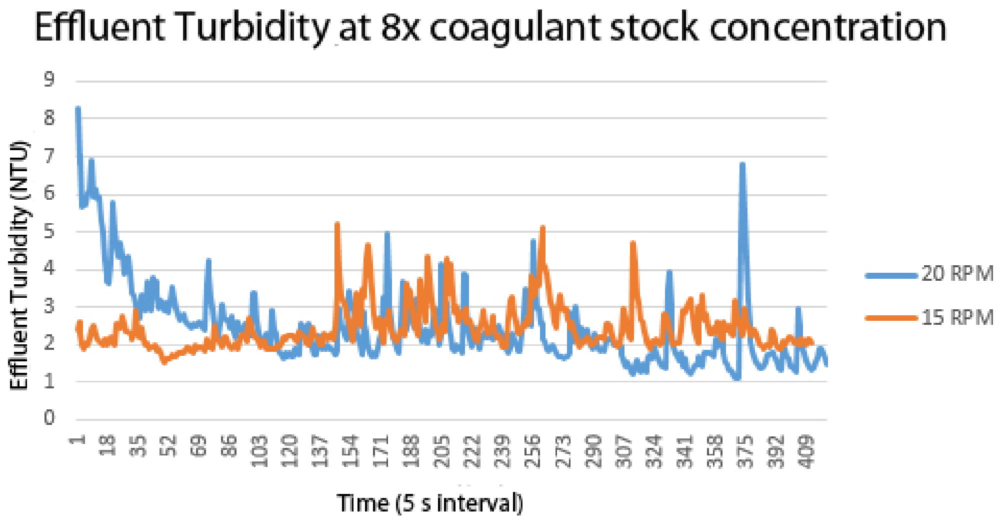
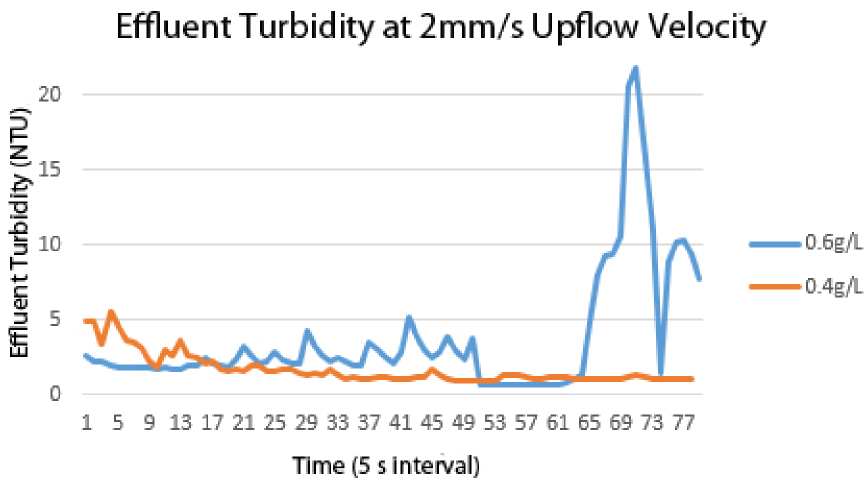


Figure 12: Effluent turbidity at intervals of 5 s with varying coagulant pump speeds. The coagulant stock concentration was increased eight times, to 0.2836 g/L, while the coagulant pump speed was varied from 20 rpm to 15 rpm.

Since the coagulant stock concentration was increased by a large amount, the coagulant pump speed was decreased from 20 rpm to 15 rpm. At 20 rpm coagulant pump speed, the effluent turbidity decreased to even lower than 2 NTU, which would make it difficult to see notable differences between a setup without a contact chamber and with a contact chamber.

The third series of experiments were run with 76 rpm water pump speed. The water pump speed was recalculated for an upflow velocity of 2 mm/s in the sedimentation tube. This change had a significant effect on the floc behavior in the sedimentation tube. In experiments 1 and 2, the floc particles did not settle easily in the sedimentation tube, which resulted in constant upflow of floc particles. This caused the floc particles to aggregate near the bend, rather than forming a floc blanket at the bottom of the sedimentation tube. After lowering the upflow velocity, a sizeable cluster of larger flocs was able to form at the bottom of the sedimentation tube. Since the water flow rate was decreased, the PID control accounted for this change, lowered the clay pump speed to compensate it, which resulted in a lower clay inflow rate. As a result, the coagulant pump speed was required to be lowered accordingly, to account for the lower flow rate through the system as adjusted by a manual flow speed change to the pump.



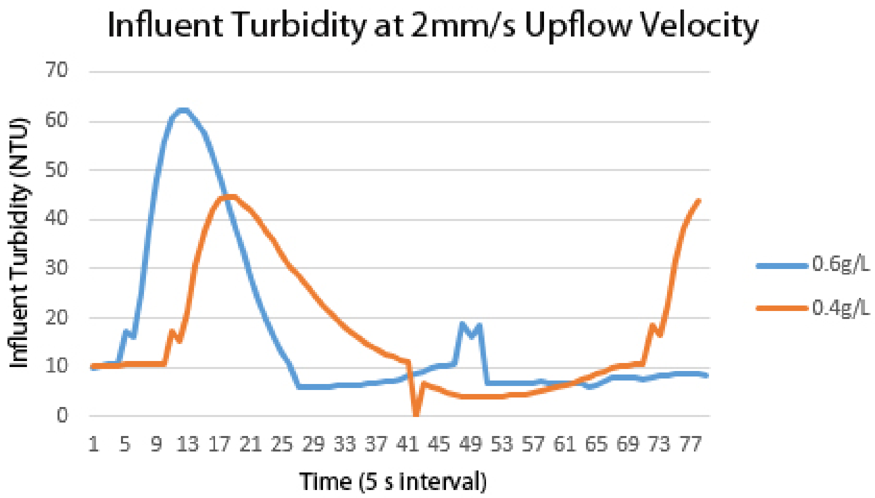


Figure 13: Effluent and influent turbidity with 2 mm/s upflow velocity, with clay stock concentration at 0.4 g/L and 0.6 g/L.

The low flow rate caused problems with the PID control. As the turbidimeter measured the influent turbidity, as the turbidity dropped below 10 NTU, the PID controller overcompensated by suddenly increasing the clay pump to 100 rpm (Figure 13). It was inferred that the clay stock was too concentrated for the low flow rate, which caused dynamic fluctuations in the influent turbidity. Therefore, the team decided to decrease the clay stock concentration from 0.6 g/L to 0.4 g/L.

It was initially hypothesized that the aggregation of a dense floc blanket within the sedimentation tube was critical in ensuring positive performance in turbidity decreases. Further experiments were run in order to assess the influence of floc presence in the system for experiments both with and without a contact chamber.

Comparing Effluent Turbidity with and without Contact Chamber

After ensuring that the influent turbidity could stabilize at 10 NTU despite initial startup complications, experiments were run to compare performance of the system with and without a contact chamber. Experiments with the contact chamber yielded higher effluent turbidity than experiments without the contact chamber. It was hypothesized that there was particle buildup in the effluent turbidimeter, so the effluent turbidimeter was emptied and refilled with distilled water. Cleaning out the turbidimeter notably decreased effluent turbidity, from approximately 4 NTU to 0.3 NTU.

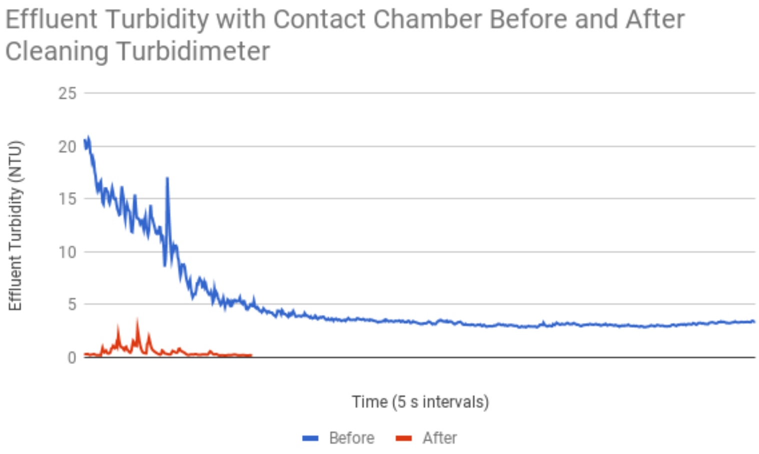


Figure 14: Change in effluent turbidity with 2 mm/s upflow velocity. Coagulant stock concentration: 0.03545 g/L in 1 L of water. Coagulant dose pumped at 20 RPM. Clay stock solution concentration: 2 g of clay in 5 L of water. Trial assessed the impacts of cleaning cuvettes in between experiments.

After observing such a great discrepancy between the effluent turbidity before and after cleaning out the turbidimeter, more tests were run with and without the contact chamber, cleaning out the turbidimeter after each trial.

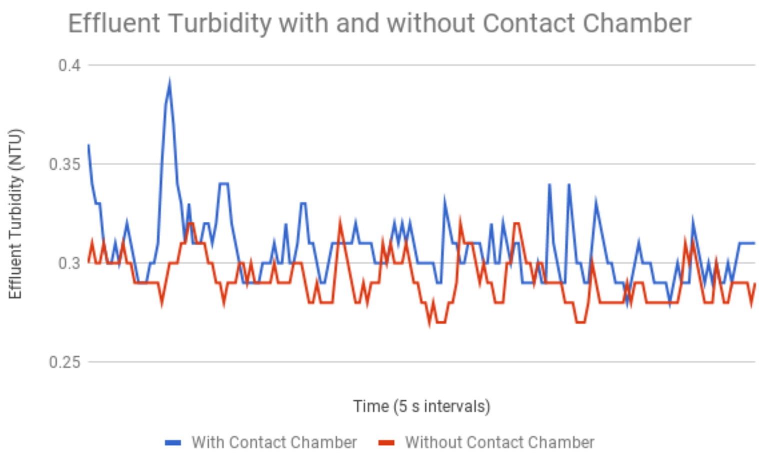


Figure 15: Change in effluent turbidity with 2 mm/s upflow velocity. Both trials with and without the contact chamber were run at the same stock concentrations. Coagulant stock concentration: 0.03545 g/L in 1 L of water. Coagulant dose pumped at 20 RPM. Clay stock solution concentration: 2 g of clay in 5 L of water. Two trials were run to assess the efficacy of a contact chamber in the experiments

The effluent turbidity with and without the contact chamber after cleaning out the turbidimeter was around 0.3 NTU (Figure 15). The effluent turbidity without the contact chamber was slightly lower than the effluent turbidity with the contact chamber.

At this point, the team realized that due to the geometry of the tube settler, a significant portion of the flow in the tube settler drained to the waste drain. Therefore, only a small portion of the plant flow actually flowed through the effluent turbidimeter, which invalidates all previous effluent turbidity results (Figure 16).

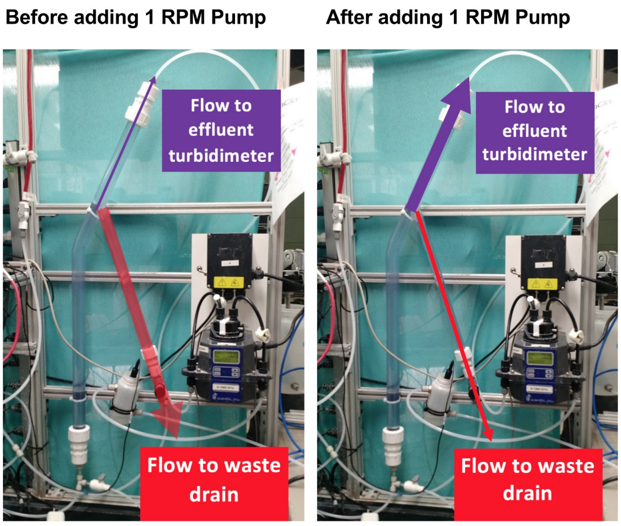


Figure 16: Before adding the 1 RPM pump, it was estimated that most of the flow up the tube settler was redirected to the waste drain. The 1 RPM pump was added to drain waste from settled flocs in the tube settler without affecting plant flow and maintaining an upflow velocity of 2 mm/s throughout the tube settler.

The next experiments were run after the addition of the 1 RPM waste drain pump. The addition of the waste drain pump resulted in a distinctly greater effluent turbidity. The effluent turbidity with the contact chamber, without the contact chamber, and with the contact chamber after cleaning out the turbidimeter was around 5-6 NTU, a significant increase from the previous experiments, in which effluent turbidity was around 0.3 NTU (Figure 17, Figure 15).

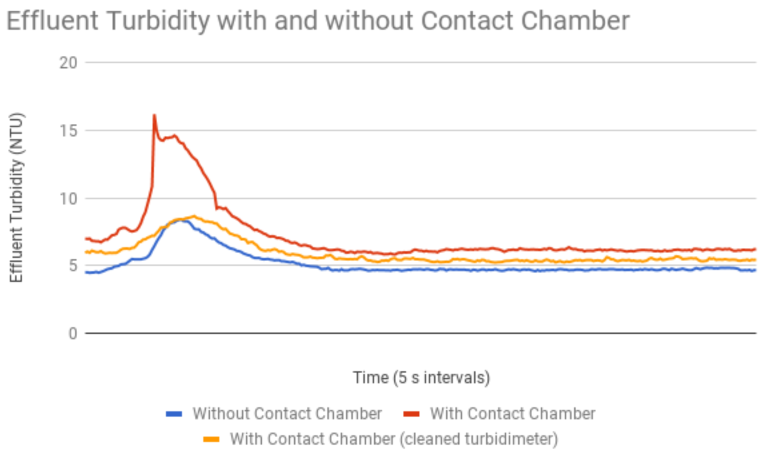


Figure 17: Change in effluent turbidity with 2 mm/s upflow velocity. All three trials with and without the contact chamber were run at the same stock concentrations. Coagulant stock concentration: 0.03545 g/L in 1 L of water. Coagulant dose pumped at 20 RPM. Clay stock solution concentration: 2 g of clay in 5 L of water. Compares impacts of the presence of a contact chamber as well as the effects of intermittent cleaning of cuvettes.

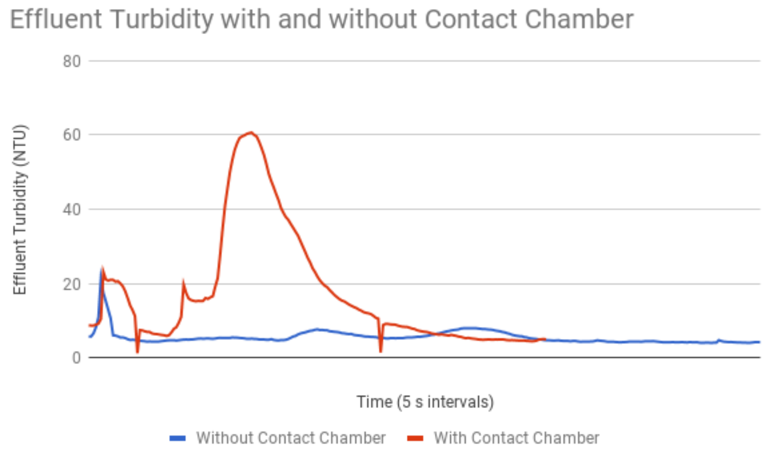


Figure 18: Change in effluent turbidity with 2 mm/s upflow velocity. Further experimentation to evaluate the performance benefits of inclusion in treatment of water to decrease turbidity. Coagulant stock concentration: 0.03545 g/L in 1 L of water. Coagulant dose pumped at 20 RPM. Clay stock solution concentration: 2 g of clay in 5 L of water.

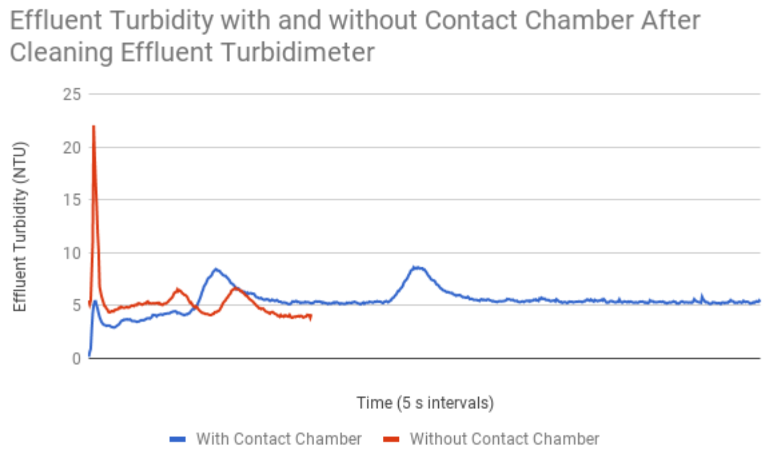


Figure 19: Change in effluent turbidity with 2 mm/s upflow velocity. Coagulant stock concentration: 0.03545 g/L in 1 L of water. Coagulant dose pumped at 20 RPM. Clay stock solution concentration: 2 g of clay in 5 L of water. Uniform procedure for both with and without the contact chamber. Effluent turbidimeter cuvettes were cleaned out in both trials.

In all trials, the effluent turbidity without the contact chamber was observed to be lower than the effluent turbidity with the contact chamber.

Discussion

The effluent turbidity without the contact chamber was significantly lower than the effluent turbidity with the contact chamber ($p < 0.001$) (Figure 15). Upon completion of several experimental trials with the contact chamber installed, the results did not support the initial hypothesis that the floc blanket was the most important factor in improving plant performance. Even though a floc blanket had formed, the effluent turbidity with the contact chamber was still greater than the effluent turbidity without the contact chamber.

In the event that the contact chamber was ineffective in decreasing the effluent turbidity, it was expected that there would be no impact to trends in the effluent turbidity as it would only be increasing the residence time of particles through the system. However, in the presence of the contact chamber, the effluent turbidity actually increased by a notable degree compared with the effluent turbidity without the contact chamber.

Undoubtedly, future experiments will be needed in order to define the source of these unexpected findings. Some sources of error that could have resulted in this relationship of the contact chamber detrimentally affecting performance included first, procedural errors in the integration of the contact chamber in between trials. An example of one of these errors was especially prevalent in initiating an experimental trial with the contact chamber being completely evacuated and full of air. The complications of this initial state were two-fold: i.) the air bubbles which traveled through the system and up through the sedimentation tube were not controlled by a designated flow rate; they rose at a much faster velocity than the surrounding water, and often broke up remaining flocs from previous trials, and thus forced the smaller floc particles upward toward the clean-water outlet, and negatively impacted the effluent turbidity. ii.) it is speculated that some of the coagulant was lost to the walls of the contact chamber as it initially filled with water, and consequently would have no attachment to the influx of clay particles as they entered the system. Without attachment of coagulant to the influent clay particles, the effluent turbidity would have been negatively affected due to the comparatively higher volume of clay stock being permitted through the process.

In addition, there was a significant difference in effluent turbidity after cleaning out the turbidimeter ($p < 0.001$) (Figure 17). Thus, the importance of cleaning out the turbidimeter should be noted when conducting future experiments.

Conclusions

The effluent turbidity without the contact chamber was consistently lower than the effluent turbidity with the contact chamber. These results suggest that the contact chamber was not effective in improving plant efficiency. However, more tests should be run to determine why the addition of the contact chamber was not only ineffective in improving plant efficiency, but actually increased the effluent turbidity, worsening the plant efficiency. Several recent modifications to the experiment setup and methods could have had an impact on the results. The addition of the 1 RPM pump at the waste drain controlled water flow through the tube settler, allowing most of the flow to flow up through the settler to the effluent turbidimeter, rather than allowing most of the flow to drain into the waste, as in previous experiments.

Future Work

More experiments will be required in order to provide insight into marginally unanswered questions. The introduction of the contact chamber was initially hypothesized to increase the number of collisions between coagulant nanoparticles and the clay particles, promoting mixing efficiency at smaller length scales in order to facilitate more frequent collisions of particles before they are sent into the flocculator. Should this not have been the case, it was expected that the contact chamber would have no noticeable impacts to treatment performance. However, experimental trials with the contact chamber in the system indicated that the contact chamber consistently negatively impacted performance.

The negative influences of the contact chamber on system performance indicated that there are many intermittent steps to follow in order to gain more accurate insight as to why the presence of a contact chamber poses as a source of decreased performance in effluent turbidity removal. The calculations of the impacts in the fluid mechanics in the system gave no indication of the introduction of a contact chamber would result in a noteworthy increase in the effluent turbidity. It is possible that there is an erroneous step in the experimental methods applied to this contact chamber. In order to resolve this uncertainty, more troubleshooting experimentation must be made. The system was tested in a variety of trials, but never presented observable failure modes. As a result, it is hypothesized that the contact chamber - either because of its geometry, where it is positioned in the system, or some other unsatisfied scientific relationship - is the source of error. Pathways of error due to these characteristics must be ruled out in order to confidently assert the accurate influence of a contact chamber in the treatment system.

Future tests include experimentally adjusting the coagulant dosage to define a more dynamic working model of the effects that marginal increases or decreases in coagulant dosed to the system have on effluent turbidity. It is also crucial for future teams to investigate the source of the unprompted spikes in clay pump speeds occur at the beginning of every initiation of PID-controlled trials. Avoiding these types of procedural error will allow for more efficient and elegant experimentation methods. The possibility must be considered that too many statistically significant variations between the trials exist, likely due in part to presently misunderstood influences that the start-up spikes might have on particle collisions and effective mixing.

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Semester Schedule

Task Map

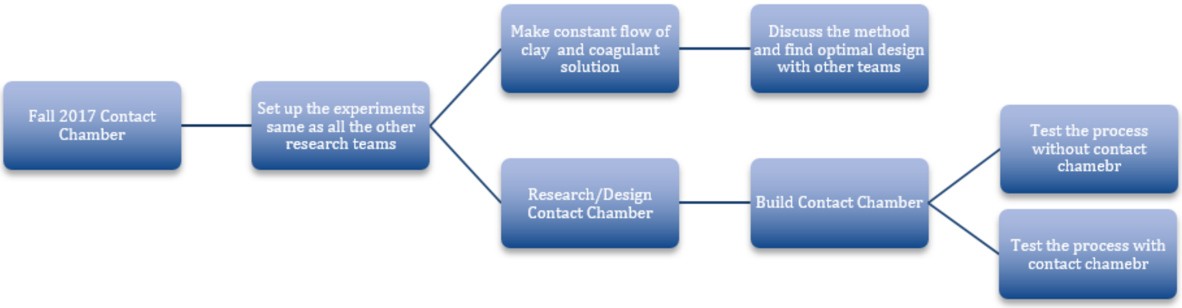

Figure 20: Task Map

Task List

1. Set up experiment (9/23-9/27)
   (a) ✓Set up coiled flocculator, sedimentation tube and pumps. [Cheer, Yeonjin, Ben]
   (b) ✓Connect tubing and check that all connections are watertight. [Cheer, Yeonjin, Ben]
2. Formulate stock solutions. (9/27-10/22)
   (a) ✓Determine the starting concentration of clay stock solution. [Cheer, Yeonjin, Ben]
   (b) ✓Use PID control to regulate inflow of clay, resulting in a constant target turbidity of 10 NTU. [Cheer, Yeonjin]
   (c) ✓Determine the concentration of coagulant stock solution to reduce the effluent turbidity to 2 NTU.[Cheer, Yeonjin, Ben]
   (d) ✓Run experiments without the contact chamber and establish control parameters.[Cheer, Yeonjin, Ben]
3. Contact Chamber (10/23-11/8)
   (a) ✓Design contact chamber. Set the length of the contact chamber to be approximately 10 times the diameter.[Ben, Yeonjin]
   (b) ✓Fabricate contact chamber using a clear pipe and sealing it with PVC caps. [Cheer]
4. Conduct experiments with Contact Chamber (11/11-12/1)
   (a) ✓Install contact chamber in experiment setup. Coagulant, water, and clay should flow into contact chamber, and mixture from contact chamber will flow into the coiled flocculator. [Ben]
   (b) ✓Test the process with the contact chamber.[Yeonjin]

Report Proofreader: Cheer Tsang

Manual

Experimental Methods

1. Begin preparatory procedures
   - Open valves to raw water and waste streams
   - Power on all three pumps: Coagulant, Clay, and Water
2. Run clay solution mixer
3. Set raw water and clay pump speeds manually
4. Begin ProCoDA program
   - Run coagulant solution until influent turbidity averages 10 NTU
5. Run until a steady-state floc blanket is achieved
6. Track changes in the effluent turbidity
7. End experiment
   - Turn off clay pump using ProCoDA.
   - Turn off all three pumps: Coagulant, Clay, and Water.
   - Close valves to raw water and waste streams.

ProCoDA Method File

Set Points

Table 2: Summary of set point parameters in the experiment operations controlled by ProCoDA

Set Point	**Operation Type**	**Value**
OFF	1	0
ON	1	1
Turb Target inf	Constant	10
Turb Target eff	*Estimate	2
P	Constant	500m
i	Constant	250m
D	Constant	0
Influent Turbidimeter ID	Constant	2
Influent Turbidity	Variable	10
Effluent Turbidimeter ID	Constant	1
Effluent Turbidity	Variable	2
Pump Control (Clay)	Variable	N/A
Pump Control (Coagulant)	Manual	10 RPM

States

Table 3: Summary of state parameters

State	Description
OFF	Default state for the experimental apparatus while not recording experimental results. Controls the PID controlled clay pump for the plant.
PID Control	Switching from the OFF state to PID Control powers the clay peristaltic pump into the plant. This flow rate is adjusted autonomously by the PID program responding to variations in the influent turbidimeter. The raw water, coagulant stock, and waste pumps are all adjusted by manually by hand based upon previous calculations.

Current System Concentrations 11/20/17

In [21]:
```
#15RPM for Coagulant Pump, 76 RPM Water
StockCoag_Conc = (0.2836/4) * (u.g/u.L) #Coaglant flowing from stock
TotalSystem_Flow = 64.67 * (u.mL/u.min) #Raw Water + Clay + Coagulant
Q_coag = 1.49* (u.mL/u.min)
C_plant= ((Q_coag*StockCoag_Conc)/TotalSystem_Flow).to(u.mg/u.L)
print('The coagulant concentration throughout the system in this trial is ' +ut.sig(C_plant,4)+ '.')
```

```
The coagulant concentration throughout the system in this trial is 1.634 mg/l.
```

In [22]:
```
x = 1.3/5
x
```

Out[22]:
```
0.26
```

Weir System Calculation

In [23]:
```
Sixteen_RPM_Conversion = 0.8 #mL/revolution
WaterSpeed = 1 #revolutions per minute
Q_Waterw = (WaterSpeed * Sixteen_RPM_Conversion)*(u.mL/u.min)
print('The flow of water out of the weir with sixteen tube is ' +ut.sig(Q_Waterw,4)+ '.')
percentage_lost=(Q_Waterw/Plant_Flow)*100
print('The percentage of water lost through weir is ' +ut.sig(percentage_lost,4)+'%.')
```

```
The flow of water out of the weir with sixteen tube is 0.8000 ml/min.
The percentage of water lost through weir is 1.209%.
```

In [24]:
```
YB_RPM_Conversion = 0.149 #mL/revolution
WaterSpeed = 1 #revolutions per minute
Q_Waterwyb = (WaterSpeed * YB_RPM_Conversion)*(u.mL/u.min)
print('The flow of water out of the weir through YB tube is ' +ut.sig(Q_Waterwyb,4)+ '.')
percentage_lost=(Q_Waterwyb/Plant_Flow)*100
print('The percentage of water lost through weir is ' +ut.sig(percentage_lost,4)+'%.')
```

```
The flow of water out of the weir through YB tube is 0.1490 ml/min.
The percentage of water lost through weir is 0.2252%.
```

Figure 21: This is an image of a sample of the calculations made in order to define experimental procedures