Countercurrent Stacked Floc Blanket Reactor

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Fall 2015

Abstract

The presence of contaminants such as arsenic and fluoride in drinking water is a major health concern rural communities around the world. Some of the most severe cases are in South-Asian countries such as such as India and Bangladesh, several regions in South America, and Africa [1]. Arsenic and fluorine are natural occurring widely distributed throughout the environment and are highly toxic in inorganic form. People in these parts of the world are exposed to elevated levels of inorganic arsenic through contaminated groundwater, which is often used for drinking, food preparation, and irrigation. Long-term exposure to these inorganics can lead to chronic poisoning, severe cases of which may lead to organ failure and internal hemorrhages[2].

A previous research team was able to successfully remove arsenic from contaminated groundwater by running the water through a sand filter in which the sand was coated in a coagulant, specifically polyaluminum chloride (PACl). This process, however, required frequent filter backwashing due to clogging seen through large pressure differentials. Despite being able to successfully remove arsenic from contaminated groundwater, the process was deemed inefficient due to its excessive consumption of treated water.

A potential solution to this problem of water wastage is to utilize a facet of AguaClara's sedimentation tanks--the floc blanket. The floc blanket is a consistently suspended and highly concentrated collection of flocs in sedimentation tanks. The Countercurrent Stacked Floc Blanket Reactor (CSFBR) team is researching to see if heavy metals such as arsenic and fluoride can be removed from contaminated waters by running contaminated water through multiple floc blankets, which have been previously loaded with the coagulant PACl.

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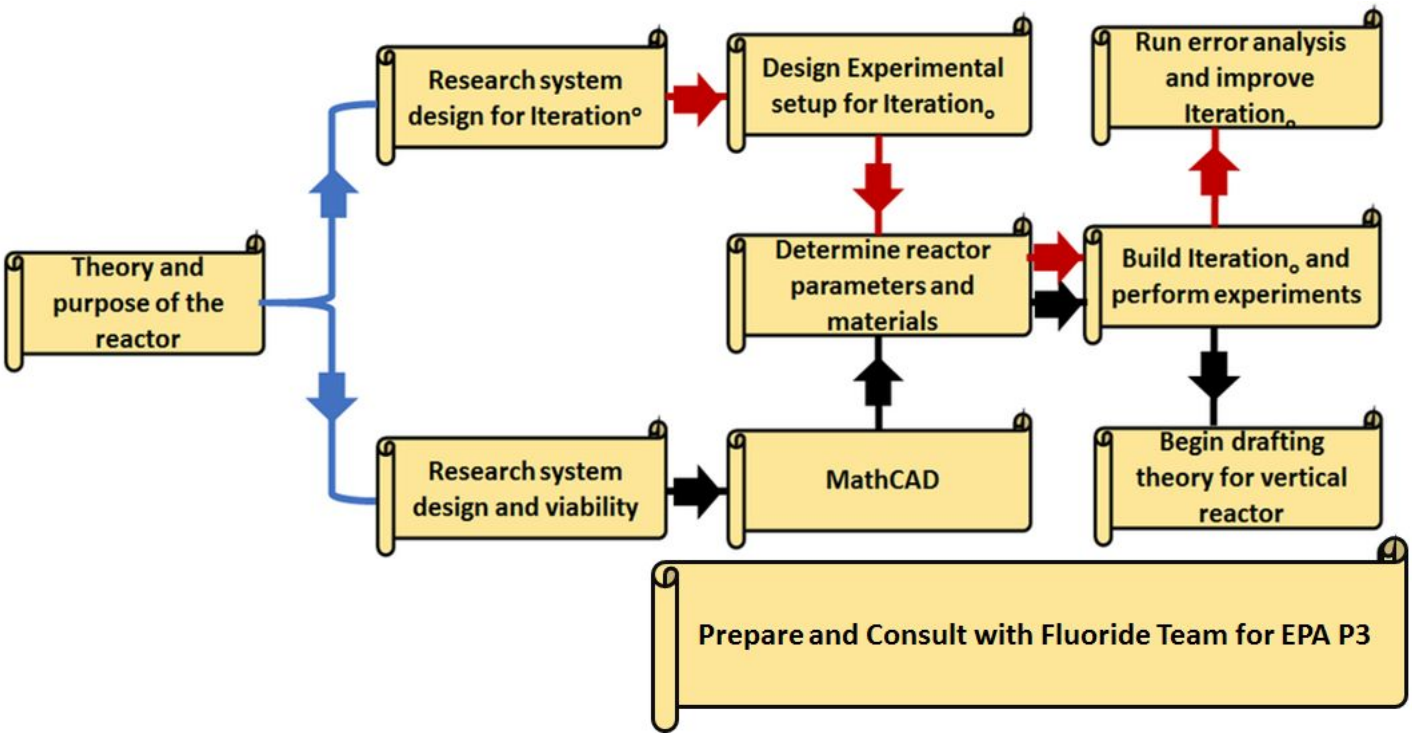

Task List

Task Map

Detailed Task List

Week 1: Monday 9/7 & Wednesday 9/9

Understand the theory and background of the reactor - Team

- i. Consult with Amiel and Monroe about the direction of the project
- ii. Discuss reactor design to ensure the team is on the same page
- iii. Identify key challenges and tasks for the following semester

Create an organized task map- Team

- i. Plan for a construction team and a theory team

Week 2: Monday 09/14 & Wednesday 09/16

Research theory/focus on viability of Venturi effect - Christine, Amlan

- i. Familiarize members with governing equations
- ii. Determine theoretical pressure drop using arbitrary parameters
- iii. Perform necessary calculations to begin designing reactor in horizontal series
- iv. Upload necessary documents in drive to serve as resources for the final report

Begin designing experimental setup - Mickey, Cindy

- i. Make first proposal of setup design by 09/28
- ii. Consult CEE machine shop for design and scaling
- iii. Aim to draft first proposal by 9/28
- iv. Decide on the size of tanks and scale rest of the setup to them
- v. Look into parts for ordering/assembly
  - a. http://www.mcmaster.com/

Week 3: Monday 09/21 & Wednesday 9/23

Research Report DUE 9/25

Proofreader: Christine

Begin modeling calculations in MathCAD - Christine, Amlan

- i. Familiarize team members with the program
  - a. Arrange a meeting with Serena
- ii. Begin translating calculations into parameters

Work on first setup proposal – Mickey, Cindy

- i. Completed draft on paper of reactor in horizontal series
- ii. Compiled list of parts necessary
  - a. Minimum number of pumps?
  - b. Material to be used?

Week 4: Monday 9/28 & Wednesday 9/30

Meeting with Monroe 9/30 3:00 - 3:30

Discuss “iteration 0” design with Amiel and Monroe- Team

i. Identify potential problems

ii. Discuss steady state and non-steady state conditions

iii. Purpose of initial experiments: Team Task

We are interested in testing the feasibility of using three consecutive floc blankets for the eventual purpose of treating metals like Fluoride and Arsenic without the use of backwash intensive sand filters.

Translate sketches of the proposed process to detailed diagram - Christine, Amlan

i. Continue translating design parameters into MathCAD

Use diagram to tweak first setup proposal – Mickey, Cindy

i. Consult other experts, such as Casey

Week 5: Monday 10/5 & Wednesday 10/7

Research Report DUE 10/9

Proofreader: Mickey

Decide on and start ordering materials – Mickey, Cindy

i. Order materials from mcmastercarr

Focus on report writing, emphasizing theory and calculations - Christine, Amlan

Week 6: Monday 10/12 & Wednesday 10/14

Fall Break 10/12

Begin assembly of horizontal series reactor- Team

Begin running first tests - Team

i. Compare results to calculations

ii. Take pictures of observations

iii. Create an error analysis

Symposium Powerpoint - Team

Week 7: Monday 10/19 & Wednesday 10/21

Symposium Week

Midterm Peer Evaluation Form Due 10/23

Continue running tests - Team

i. Take careful note of time to empirical steady state

ii. Take pictures of observations

iii. Create an error analysis

Week 8: Monday 10/26 & Wednesday 10/28

Redesign and rework horizontal reactor design - Mickey, Cindy

i. What worked with the design?

ii. What did not work with the design?

iii. Can we make the design more efficient?

a. Less materials, smaller, etc.

Look into literature relating to Floc Blanket Reactor - Christine, Amlan

i. Is there previous research that we can use?

ii. How can we justify our horizontally oriented design?

Week 9: Monday 11/2 & Wednesday 11/4

Research Report Due 11/6

Proofreader: Amlan

Begin drafting vertical series reactor - Christine, Amlan

i. Consider horizontal series reactor

ii. Consider material

a. Any substitutions? Resizes? Redesigns?

Improve current horizontal design - Mickey, Cindy

i. What can be done differently next time

ii. Propose future adjustments

Focus on report writing, emphasizing experimental tests and results - Mickey, Cindy

Week 10: Monday 11/9 & Wednesday 11/11

Meeting with Monroe Monday 11/09 3:00 - 3:30

Discuss horizontal series reactor design with Amiel and Monroe- Team

i. Results/ conclusion/ suggestions

ii. Moving forward to vertical series reactor design?

Look into spectrometer and turbidimeter

i. Determine tubings and new setup

ii. Determine dye and data collection methods

Look into literature regarding dye tracers -Christine and Amlan

Week 11: Monday 11/16 & Wednesday 11/18

Research Report Due 11/20

Proofreader: Cindy

Order Dye and Run tests - Micke, Cindy

Prepare system for turbidimeter and spectrometer readings

Look into vertical series reactor- Christine, Amlan

i. Details including sizes/ lengths, geometries, flow velocities, head losses

ii. Estimate assembly cost

Research Repor - Team

Week 12: Monday 11/23 & Wednesday 11/25

Thanksgiving Break

Do great things and RELAX - Team

Week 13: Monday 11/30 & Wednesday 12/2

FINAL Draft Research Report Due 12/4

Proofreader: Everybody

Peer Evaluations Due 12/4

Research Report and Final Presentation- Team
Week 14: Monday 12/07 & Wednesday 12/09
FINAL Research Report Due 12/9
Proofreader: Everybody

Introduction

Presence of inorganic contaminants (such as arsenic and fluoride) in water is a major health concern for rural communities around the world. Arsenic is a natural component widely distributed throughout the environment, however it is a known carcinogen and is highly toxic in its inorganic form. Likewise, fluoride is also toxic and is known to inhibit brain development. These chemicals are known to contaminate groundwater sources in countries such as India, Vietnam, and Argentina and exposure to these compounds ultimately decrease living standards and increase mortality rates.

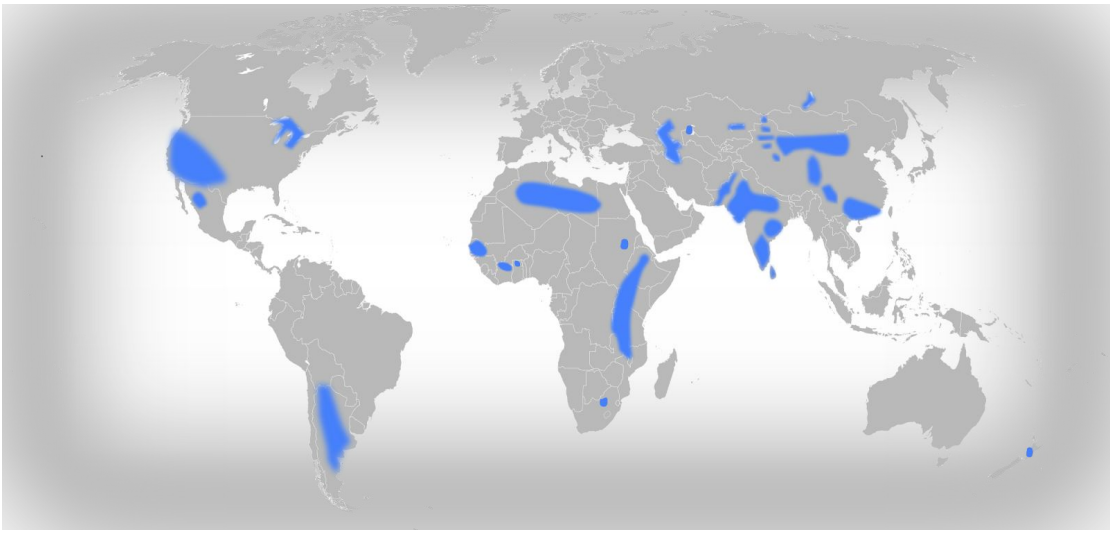

Figure 1: Groundwater fluoride contamination areas.

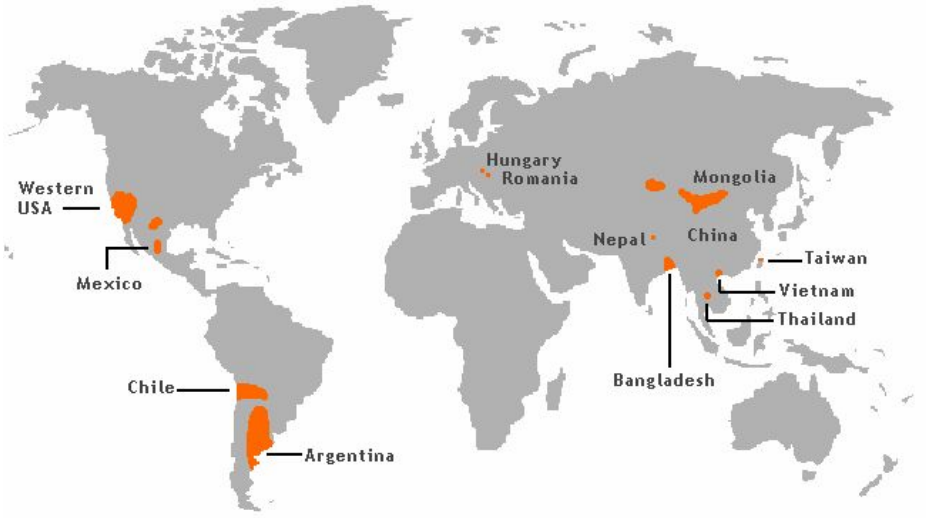

Figure 2: Groundwater arsenic contamination areas.

A conventional method of removing pollutants such as arsenic and fluoride from water is by using sand filters.Despite its effectiveness, the treatment process leaves the sand filters clogged, and thus these filters need to be flushed out frequently. The backwashing ultimately wastes a significant amount of water, and disrupts the treatment process. In order to reduce water consumption during the cleaning process, a new design was proposed. A set of floc blanket reactors in series could be used to coagulate and filter out organic contaminants; this proposal would ultimately replace the sand filter process and maintain a continuous reactor flow.

The aim of the CSFBR team this semester is to develop a horizontal series of reactors, each with its own floc blanket, and determine the viability and effectiveness of this purification process. In this design, the floc blanket heights will be controlled by floc weirs, one in each reactor, as the water circulates throughout the system. The goal is for the flocs to begin at the last reactor, and eventually overflow into the rest of the system by wasting them into the previous reactor. Ultimately, the flocs will be removed from the system after the last reactor, and with it, inorganic chemicals like arsenic and fluoride.

Literature Review

A study was conducted by Najm, Snoeyink and Richard at University of Illinois Urbana Champaign to observe the effect of the addition of powdered activated carbon (PAC) to upflow floc-blanket reactors and record the adsorption of natural and synthetic organic chemicals. A floc-blanket reactor was operated with PAC addition for the adsorption of 2,4,6-trichlorophenol (rcP) and natural organic matter from one groundwater and two surface waters under laboratory and field conditions, respectively. It was observed that while the hydraulic residence time in the floc-blanket reactor varied from 15 to 30 min, the carbon residence time ranged from 9 to 34 h. This is due to the high concentration of suspended solids in the floc blanket, which ranged from

1200 to 8700 mg /L [3]. Comparison between the extent of TCP adsorption through the floc-blanket reactor and the equilibrium adsorption isotherms of TCP on PAC showed that the maximum adsorption capacity of PAC for TCP was utilized in the reactor. However, this study showed that the maximum adsorptive capacity of the carbon in a continuous process is dependent on the influent adsorbate concentration. This was in agreement with isotherm studies conducted with varying initial TCP concentration. A valuable conclusion than can be drawn from this experiment is that the maximum PACl adsorption capacity for natural organic matter was also achieved in the floc-blanket reactor.

Another performed by Ingallinella, A., et. al., which closely resembles the process that is being replicated in the lab, determines the effect of different concentrations of PACl on the removal of arsenic and fluoride [4]. A treatment line which consists of acidification (to pH 6.4–6.6), followed by the addition of PACl (doses of 100 to 125 mg/L), followed by alkalinization (to pH 7.2–7.6) and finally rapid filtration, was tested. In raw water, arsenic and fluoride concentrations ranged from 70 to 90 20 µg/L and from 2.8 to 3.1 mg/L, respectively. This treatment process allowed arsenic and fluoride to be jointly removed, efficiencies reached ranged from 75 to 85 % for the arsenic and 50 to 55 % for fluoride. Arsenic concentrations in treated water were <20 µg/L and fluoride concentrations remained at 1.3 to 1.7 mg/L. an idea of the concentration of PACl that should be used

Additional study, completed by Hurst, M., et. al., concerning the parameters of steady-state floc blanket reactors, designated several possibilities for structuring the testing of the proposed process [6]. It was observed that an upflow velocity of 1.2 mm/s would be optimal only until an influent turbidity level of 500 NTU. A turbidity level greater than 500 NTU would require an upflow velocity of 0.8 mm/s for optimal floc blanket performance. Optimal floc blanket performance is defined to be where “the bed of particles is suspended in a floc blanket.” After reviewing this report, the team noted that tests with influent turbidity levels greater than 500 NTU should be conducted and prior to such tests, that all calculations must be adjusted to an upflow velocity of 0.8 mm/s.

Theory and Design

The final iteration of this project will be a set of three reactors aligned atop one another - the motivation of this arrangement is so that the vertical setup can utilize gravity to drive the flocs downward, while an influent jet stream can drive the flow of water upwards from one reactor to the next. Although implemented in this design, pumps would not be a part of the final iteration, so that the design would be affordable and sustainable for resource limited communities in the global south.

The three reactors in series will each have a floc weir, which will not only maintain the height of the floc blanket, but will also cause an overflow. The flocs that overflow at the highest reactor (reactor 3) will be fed into the influent stream of the middle reactor (reactor 2), which will then accumulate the floc weir at reactor 2, and then be fed into the influent stream of the lowest

reactor (reactor 1) - reactor 1 is where the flocs are wasted out of the system. In this theoretical model, the cleanest water will emerge from reactor 3, where fresh PAC will be added, while the water will enter reactor 1 where the oldest PAC in the system will be wasted.

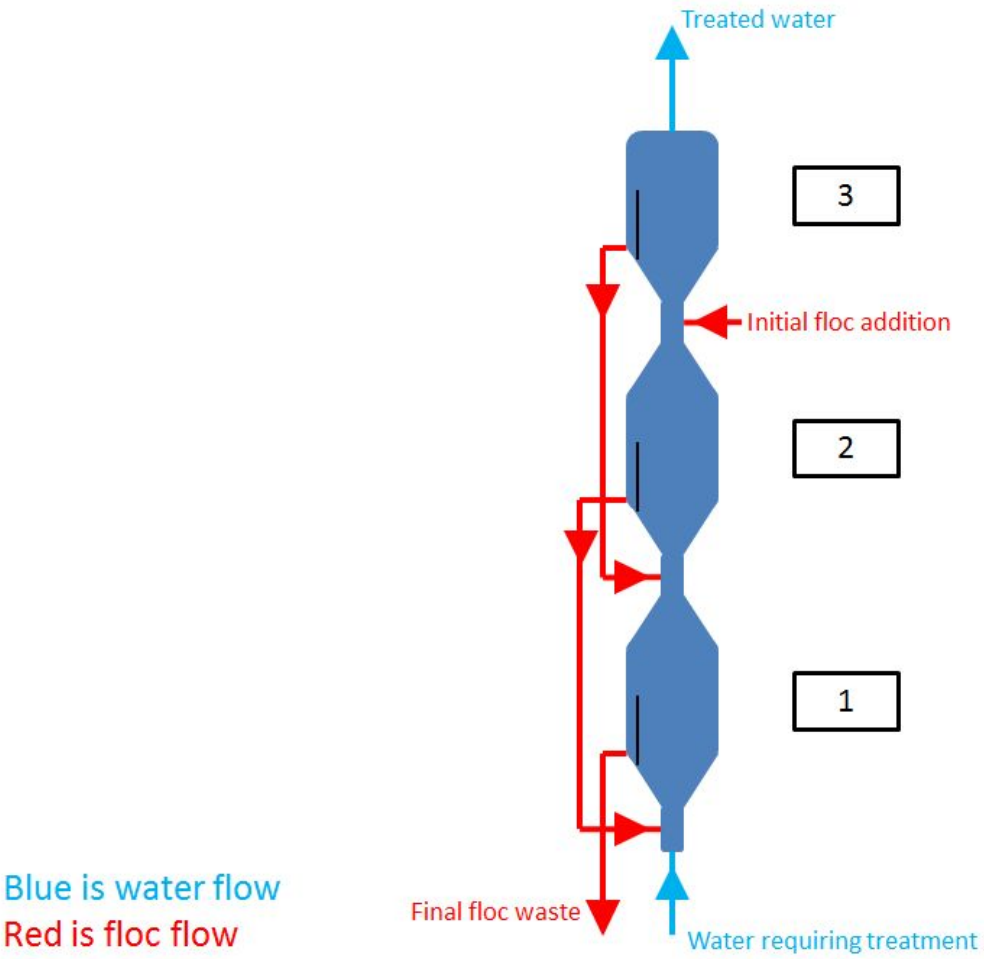

Figure 3: Final design for Countercurrent Stacked Floc Blanket Reactor.

A key component to the final design, to be implemented in Spring 2015, includes the addition of a venturi nozzle before the influent jets of each reactor. The venturi effect is used in order to create a pressure difference large enough for the accumulated flocs to flow downwards to an otherwise higher pressure region. The relationship between pressure and velocity is given as the following expression:

$$P_1 - P_2 = \rho/2\,(v^2_2 - v^2_1)$$

Where P_1 and P_2 represent the inlet and outlet pressures of the constriction, v_1 and v_2 represent the corresponding flow rates, and ρ represents the density. From the expression, as

velocity gradient increases, so does the pressure gradient. This relationship can be used to manipulate the constriction pressure. By increasing the velocity within the constriction, the pressure at that point will decrease. Theoretically, with a small enough constriction, the pressure drop will be enough to create a vacuum-like inlet to take in the fed flocs from the reactors above.

Methods

Reactor

Because the ultimate goal of the team is to utilize gravity and the Venturi effect to allow for flow of water and flocs, the first sketches arranged three reactors in series vertically. However, it was later determined that the goal of the team for Fall 2015 would be more focused on the feasibility of countercurrent flow between flocs and water and not on making use of gravity to aid flow. Therefore, the team rearranged the three reactors in series horizontally. Two pumps, one for floc flow and one for water flow, would be used instead of gravity and the Venturi effect.

Weir

Based on the the theory, the flocs and water must flow separately and in opposite directions. The following considerations were discussed when planning the design of the weir:

1) Opposite, or counter-current flow, would require the weir to be designed such that a tube transporting flocs between reactors could be installed on to the weir.
2) Because the aim is to get a physical split between the flocs and water within each reactor, the flocs must be maintained at a constant height. Furthermore, this height must not be too close to the reactor exit to reduce the amount of flocs in the water flow.

Based off these considerations, the team determined that the weir was to be installed at approximately 70 % of the reactor height. At this level, the floc blanket would have enough space to develop and collect, while still being far enough from the reactor top to not flow out with the water effluent. .

The team's first proposal of a weir design was to install a pipe with a diameter one-half of the reactor's diameter.in the center of each reactor. However, this proposal would have required a significant amount of assembly and modification. Furthermore, this design would put constraints on the reactor and weir diameters. After further analysis, it was determined that in order to connect the tubes transferring the flocs to each reactor, the following steps were required:

1) Drilling an opening in the reactor wall to insert the tube.
2) Creating a connection into the weir pipe to allow the passage of flocs.

The team ultimately determined that placing the floc weir inside the reactor was not feasible. The team's next proposal looked into determining how to incorporate the weir as a part of the external surface of the reactor. Further consultation with project advisors led the team to simplify the weir design for the first set-up proposal. To reduce the amount of drilling and pipe

modifications, it was decided that a 1 inch wye fitting would be used as a weir for each reactor. In this way, instead of having a single piece of pipe as the reactor and a smaller pipe inside as the weir, the reactor would be a composition of 2 pipes, connected by a wye pipe in between to act as a weir.

Flow/Tubes

The aforementioned theory requires that flocs and water move separately. The team determined that the flocs and water must exit through separate tubes. Based on that information,the location for each inlet and outlet connection for water flow was determined.
The following considerations for water flow were discussed:

1) Water flow can re-suspend flocs in the reactor.
2) Water, at relatively high velocities, can break up flocs and carry them into the effluent.
3) Water must flow between each reactor and with a minimal amount of flocs.

The team determined that water would enter each reactor through the bottom of the reactor, to re-suspend flocs. Water entering would be kept at velocity of 1 mm s^{-1}. There would be no sudden expansions or contractions inside the reactor to maintain a constant flow velocity. With these specifications, water would then leave each reactor from the top. With the low flow velocity, the weir below would facilitate the separation between the flocs and water, allowing the flocs to build up and fall over the weir tube. From there, the flocs would be pumped out by the floc tubes.

Concentration and Flow Rate of PACl

Before running experiments with the reactor design, the team had to first determine a maximum concentration of PACl feed in order to maintain a standard water pH. The alkalinity of water at Cornell University was given to be 1.33 mmol $CaCO_3$/L [5]. Because $CaCO_3$ can accept two protons, approximately 2.66 mmol of H^+ can be neutralized for every liter of water. For these calculations, the target water pH was set to 7 and the two assumptions made were that the water pH was initially at 7 and that 1 mole of PACl will donate three protons. Based off this, the maximum concentration of PACl was determined to be 0.887 mmol/L.

The density of PACl mixture was determined by multiplying the max concentration of PACl with the molar mass. Finally, with the density, flow velocity, and cross sectional area of the piping (⅜ in), the final mass flow was determined to be 0.45 mg/min. The detailed calculations can be found in the AguaClara S: Drive.

Flocculator Assembly

The purpose of the flocculator was to encourage mixing and increase particle collisions so that sizable flocs can be created and enter the reactor. The design was determined by using the

principles of velocity gradients G and the dimensionless mixing parameter Gθ [5]. The θgoal, residence time, was determined to be 29.502 min. Using the relationship:

$$L = \theta_{goal} \frac{Q}{AD}$$

Where L is the length of the tubing, A is the cross sectional area of the tubing, and *D* is the diameter of the flocculator tubing, the total length of the tubing for the flocculator was determined to be 45.845 ft. The length of the flocculator body was determined to be 1.09 ft. The tubing diameter was originally ⅜ in but was reduced to ¼ in, in order to prevent flocs from settling at the bottom of the coils. The assembled flocculator is illustrated in Figure 4. The feed entering the flocculator was a mixture of 2400 mg/L clay combined with .8867 mmol/L of PACl.

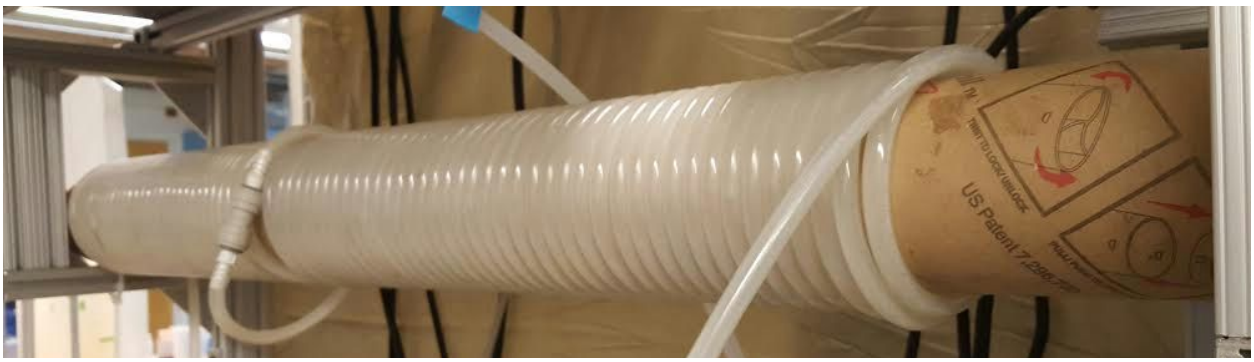

Figure 4: The assembled flocculator

Reactor Assembly

After the team finalized the calculations and parameters, the reactor was assembled. The clear PVC tube above the wye fitting was cut to 0.07 m. The clear PVC tube under the wye fitting was cut to 0.21 m. The two PVC tubes were glued into the wye fitting, and the total reactor spanned a length of 0.39 m (Figure 5). The angled PVC pipes attached to the wye fittings are meant to serve as the floc weirs. The flocs are planned to exit this outlet as the rest of the water passes through. The bottom of the reactors are plugged with an expansion pipe (Figure 6). This expansion is meant to reduce losses and provide an upstream velocity of water for circulation. These were constructed from a 1 inch PVC rod. Each rod is 3 cm in length. One end is an expansion and the other end is threaded for the tube fitting. The other outlets of the reactor were fitted with pressure caps (Figure 7). After the bodies of the reactors were assembled, the team began looking into connecting the various pump heads for the feed streams. The final setup is illustrated in Figure 8a and 8b. The reactors are secured onto the aluminium strut with zip ties.

Figure 5: The assembled body of the three reactors

Figure 6: A close up of the expansion pipe

Figure 7: A close up of the pressure cap

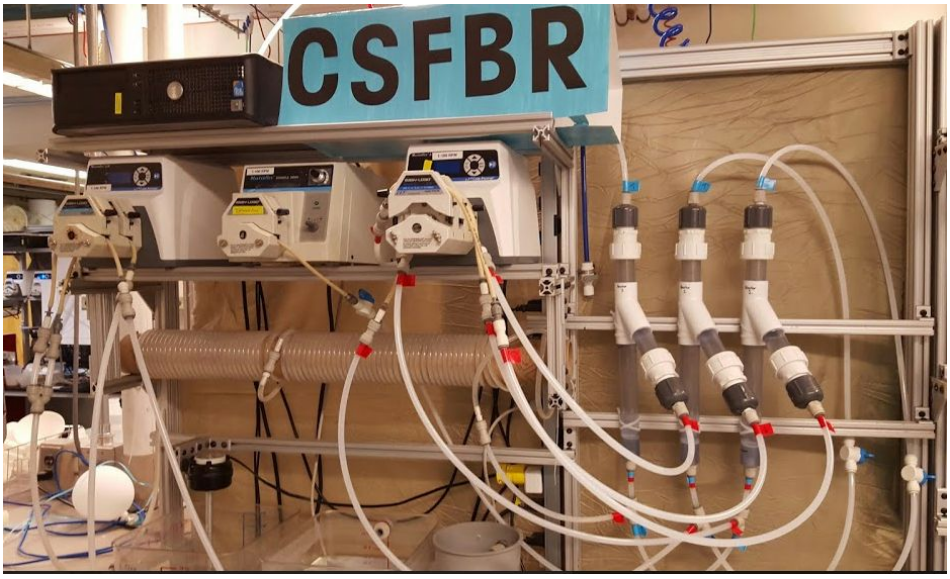

Figure 8a: The final set up of the reactor in series, suspended on aluminum struts.

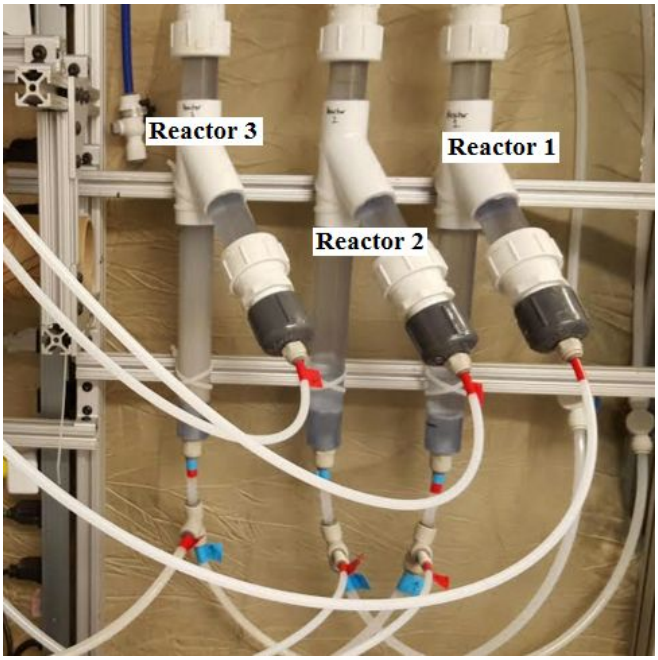

Figure 8b: The labeled reactors from the final setup

Pump Calibration

Once the flow rates and concentration of PACl, clay, and water were determined, the team calibrated the pumps. In this set up, three pumps were used. Pump 1 fed a clay and coagulant mixture through the flocculator and into the third reactor. Pump 2 pumped the influent water into

reactor 1. Pump 3 pumped the accumulated flocs in the wye fitting into their respective, following reactors. The schematics of the pumps are shows in figure 9.
The corresponding calibrations are shown in Figures 10a, 10b, and 10c.

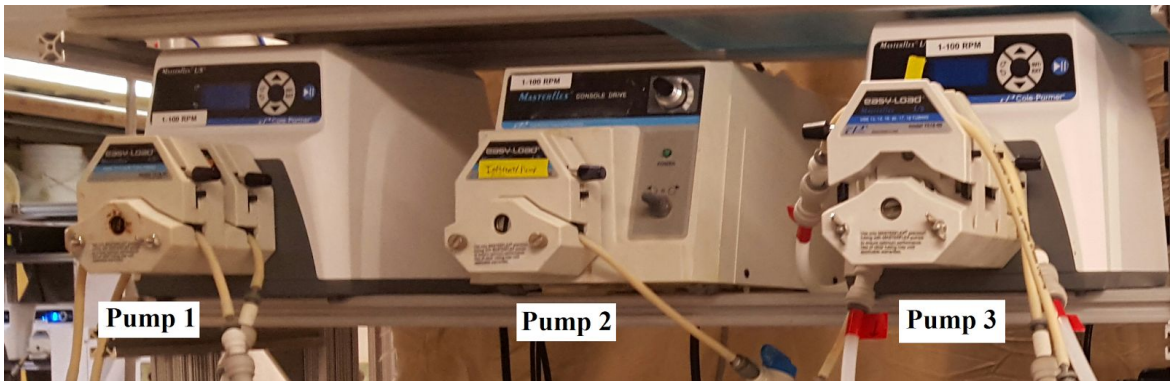

Figure 9: The setup of the pumps in the experiment

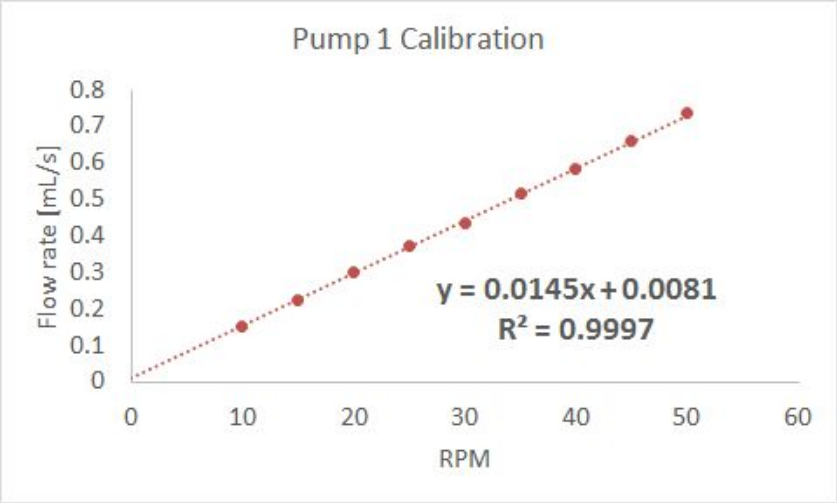

Figure 10a: Calibration for Pump 1

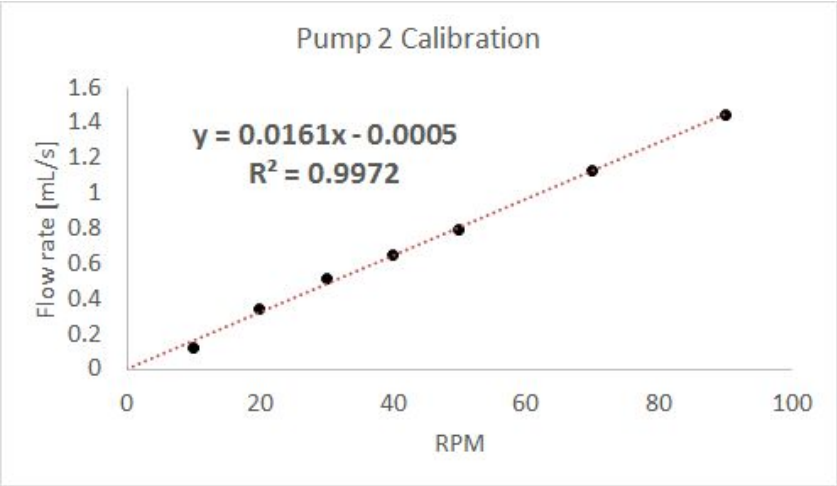

Figure 10b: Calibration for Pump 2

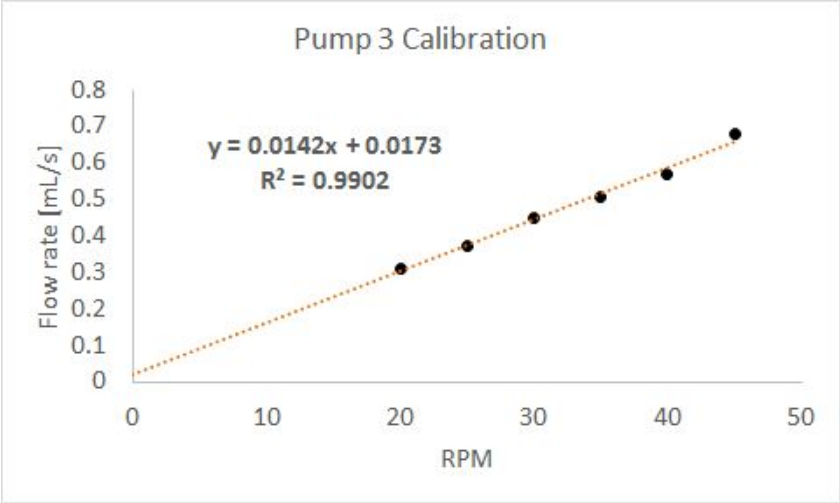

Figure 10c: Calibration for Pump 3

Experimental Testing

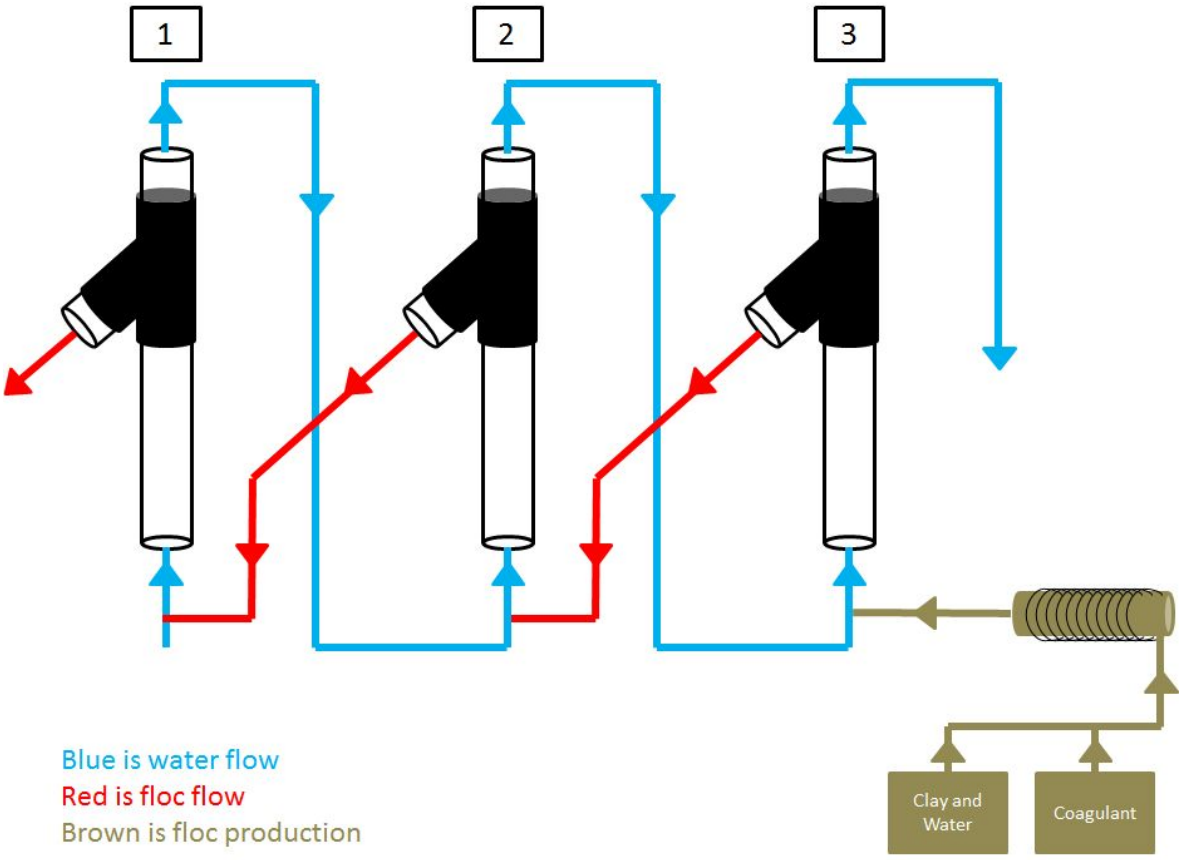

Figure 11: Initial setup for testing the formation of floc blankets.

Before testing the hypothesis that floc blankets can remove contaminants, like arsenic and fluoride, the apparatus needed to have the ability to build and maintain three floc blankets. Each reactor had an influent of water and flocs that entered from the bottom, an effluent of flocs that exited from the floc weir, and an effluent of water that exited from the top. While the total flow rate through the reactor was constrained to the reactors' dimensions and a 1 mm/s upflow velocity, the fraction of the total flow rate for each influent was not a constraint. Also, the flow rate of the effluent from the floc weirs was not a constraint. Finally, the effluent of water from the top of the reactors was not an aspect that necessitated a certain flow rate, and was therefore allowed to flow passively.

Sedimentation

The team added a clear pipe, which is connected to the top of Reactor 3 that acts as a tube settler. The pipe has an angle of 45 degrees and a length of 14.75 in. This length was determined using the following equation from CEE 4540's Sedimentation notes:

$$Vc = \frac{Vplate * S}{L\cos\alpha \sin\alpha + S}$$

Where Vc is the capture velocity (0.12 mm/s), Vplate is the upward velocity into the tube (0.707 mm/s), S is the diameter of the pipe (1 in), L is the length of the tube, and α is the angle of the tube (45 degrees). With rearrangement, the length was solved.

A T-connector was also added to connect the tube settler and Reactor 3.

Turbidimeter

In order to test the effluent concentration, a turbidimeter has been included in the apparatus. After simple testing, it has been realized that different levels of turbidity can influence concentration readings from the spectrophotometer. The turbidimeter will therefore measure the turbidity of the effluent, which will allow for corrections in concentration readings if necessary.

Spectrophotometer

The team has received a spectrophotometer from the Spectrophotometer Team, and new ProCoda software from Monroe Weber-Shirk. With a spectrophotometer, concentration of dye in the water can be measured. With these measurements, percent removal can be calculated based on influent dye concentration and effluent dye concentration. The new ProCoda software can calculate the concentration of dye in the water based on the spectrophotometer reading. The software uses linear interpolation to relate spectrophotometer readings to concentration. The spectrophotometer was added to the apparatus for the purpose of collecting data sets of dye concentration measurements at the effluent of the plant. Also, to ensure that high turbidites were not causing error in concentration measurements, a turbidimeter was also placed at the effluent, but before the spectrophotometer. With turbidity readings, erroneous peaks in measured concentrations can be ruled out when analyzing data for removal efficiency if those points can be correlated with spikes in turbidity.

During the initial installments of the spectrophotometer in the apparatus, there were issues with leaking. This was of particular concern due to the electronics that surround the device. Electronics have only recently been involved in the apparatus, so extra caution was taken to prevent any damage due to water contact. Eventually, a loose fitting was found to be the reason of the leak and was made to be a better seal with teflon tape.

The spectrophotometer and turbidimeter were added as measurement tools to the ProCoda software for easy data collection of measured concentrations and turbidites. With the software, the data is automatically entered onto a Microsoft Excel spreadsheet, along with the time at which the measurement was made.

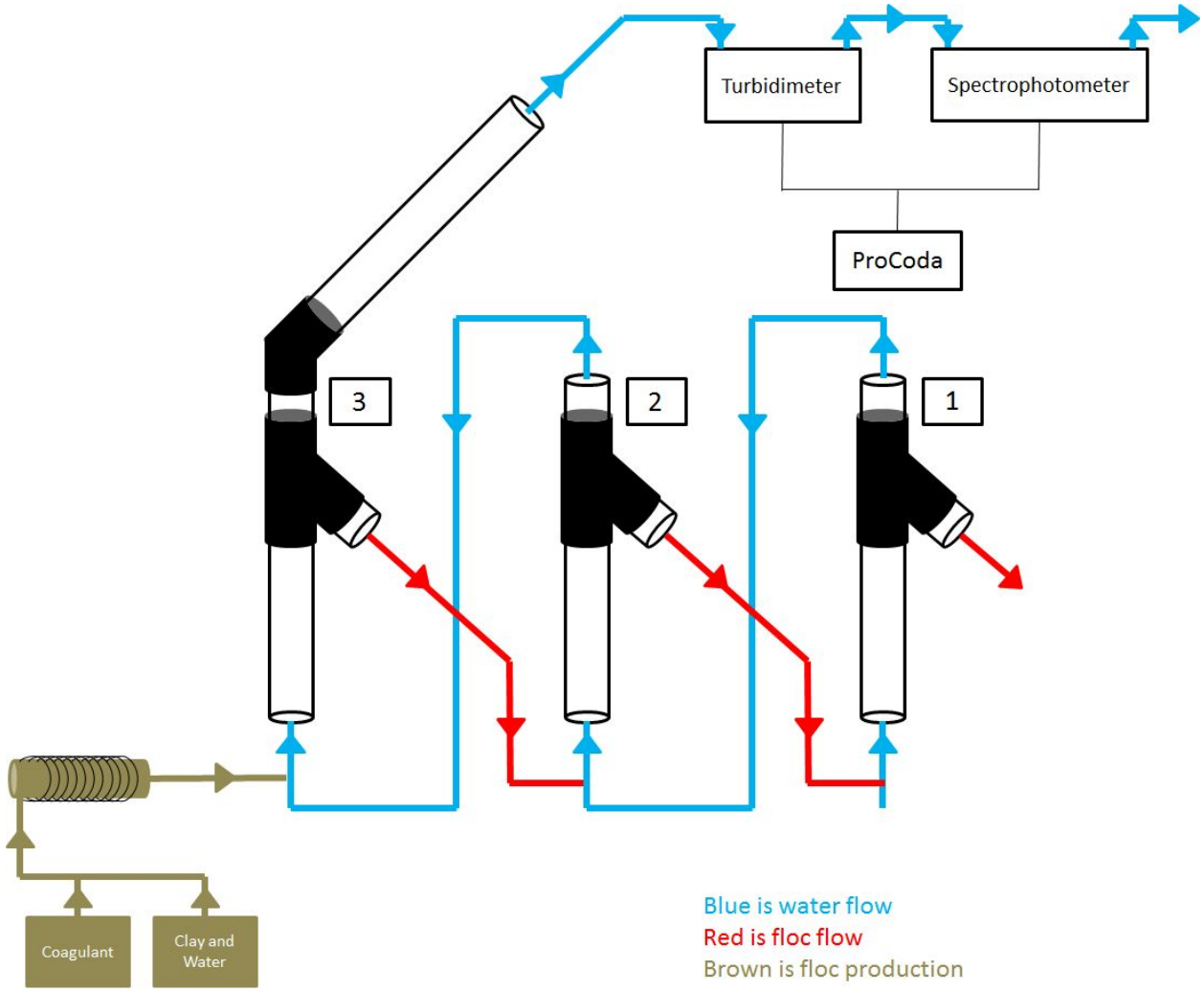

Figure 12: Final setup for measuring and recording effluent dye concentrations.

For ProCoda to linearly interpolate voltage values into concentration values, the software uses a calibration curve based on measured stock concentrations. For the that will be used in experiments, Remazol Brilliant Blue Dye, the stock concentrations measured for the calibration curve were 0, 2, 5, 10, 20, and 50 mg/L. The calibration curve is shown below.

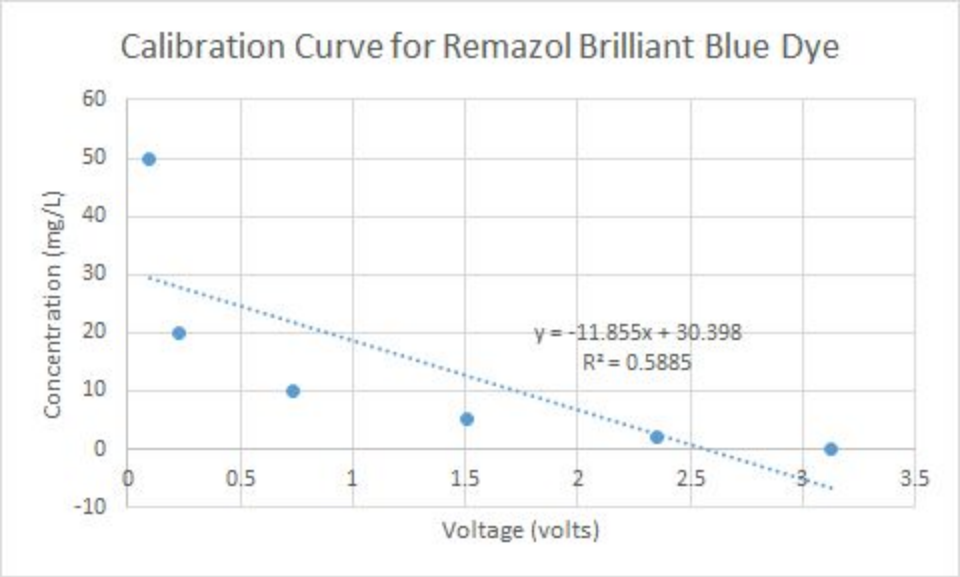

Figure 13: The calibration curve used by ProCoda to linearly interpolate concentration values in the effluent of the plant.

Due to a very low R-squared value, a metric used to measure the linearity of a set of data, recalibration will have to performed to achieve accurate concentration calculations from ProCoda.

Results and Discussion

Building Floc Blankets

Because of the novel nature of this project, arbitrary fractions were chosen. Half of the total flow rate was dedicated to the water influent, and the other half was dedicated to floc addition. This resulted in a flow rate of 0.253 mL/s for each. With results from this experiment, it could be determined whether the next experiment could be run with a higher flow rate of water, or a lower flow rate of water. The thought behind this methodology stemmed from the eventual implementation of this apparatus in the field. If the apparatus is able to operate with a higher flow rate of water, it would also be able to treat water in the field at a faster rate. The last arbitrary value was the floc weir effluent flow rate and was chosen to be 0.030 mL/s.

The system was allowed to run with these flow rates for a period of 18 hours, and during those 18 hours, each reactor was able to create and maintain a floc blanket. But due to certain apparatus restrictions, reactors 1 and 2 had more dense floc blankets than reactor 3. Reactor 3 was the only reactor that directly received flocs from the flocculator, whereas reactors 1 and 2 receive floc addition from floc weir effluent. The flow rates in reactor 3 for the floc weir effluent could not equal the flow rate of floc influent because it would cause an increase in upflow velocity in reactor 3. If the upflow velocity were to be higher than 1 mm/s, the floc blanket would

likely be unstable and flow out of the system, which would result in failure. With a lower upflow velocity in reactors 1 and 2, they were able to capture flocs of smaller diameter than reactor 3, which resulted in denser floc blankets.

Another difference between reactor 3 and reactors 1 and 2 was that only reactor 3 experienced sludge accumulation in the floc weir, whereas the floc weirs in reactors 1 and 2 maintained a consistent slide of flocs down to the exit. This was due to a difference in mass balances. Reactor 3 was receiving flocs at a much higher rate than it was removing flocs, which led to an accumulation. In reactors 1 and 2, the rate of floc addition was equal to the rate of floc removal because the flow rates of floc influent and floc weir effluent were equal.

After flushing the system, the apparatus was run for another 18-hour period to test different flow rates. With successful formation of floc blankets with previous values, an increase of water influent flow rate and a decrease in floc influent flow rate were attempted. The second set of values were 0.455 mL/s for water influent, and 0.050 mL/s for both floc influent and floc weir effluent. The goal was to not only see if a higher flow rate of water would yield successful floc blankets, but also to see if floc influent and floc weir effluent could be run at the same flow rate, while not significantly affecting the upflow velocity in reactor 3. This led to a fraction of 0.9 for water influent and 0.1 for floc influent of the total reactor flow rate. These values would also make the upflow velocity and rate of floc addition in all reactors much more similar than with the previous values.

This second set of values yielded in a failure to produce floc blankets. Due to the low flow rate through the flocculator, considerable settling was observed in the flocculator tubing, which greatly reduced the addition of flocs to the three reactors. With the lower flow rate, larger flocs were formed. This issue can be solved by decreasing the diameter of the flocculator tubing to increase velocity. But this has been seen as a tangent, and will therefore be revisited after the concept of contaminant removal through floc blankets has been tested.

The following table provides parameters from four experiments that were conducted for floc blanket formation, and some observations that were made.

Number of Experiment	Water Input Flow Rate (mL/s)	Flocculator Addition Flow Rate (mL/s)	Floc Weir Addition Flow Rate (mL/s)	Key Observations
1	0.251	0.134	0.0299	- three well-formed floc blankets - reactors 1 and 2 have more

				dense blankets than reactor 3 - reactor 3 has sludge build-up in floc weir; reactors 1 and 2 do not
2	0.455	0.500	0.0415	- no floc blanket formation - high amounts of floc settling in flocculator - some flocs in weirs; possibly remnants from last experiment
3	0.251	0.134	0.0328	- similar floc blankets to first all-night run - less settling in reactor 3's floc weir
4	0.251	0.134	0.0357	- successful floc blanket formation - floc weir effluent flow rate increased due to buildup in reactor 3's floc weir

Table 1: Summary of four experiments that hoped to successfully build a floc blanket in each reactor.

Testing with Tracer Dye

The team proposed to incorporate a colored dye within the testing procedure. Because flocs appear pale and translucent, it was difficult to track their movements as they passed through the flocculator, tubing, and reactor. In current experimental trials, the team used a portable light source to observe the floc behavior in the reactors. Unfortunately, this method was not fully effective, especially when the team was trying to make qualitative observations of the flocs passing through the tubing. The team decided to use a tracer dye to clearly trace the floc pathway. The team looked into several articles of literature analyzing various dyes and their performance with PACl.

Red Dye

The first type of dye that the team used was a red dye. This was found referenced in literature, which detailed a study of four dyes and their reactivities with PACl [7]. An aqueous solution contained the following dyes: turquoise DG, black DN, red DB-8 and orange OGR. The study showed that PACl coagulated with each of the four dyes at varying levels of efficiency. The highest reaction efficiency was observed with the turquoise DG dye, which resulted in a PACl

concentration drop from 95.4 mg/dm^3 to 0.6 mg/dm^3. The lowest reaction efficiency was observed for the red DB-8 dye, which decreased the concentration from 107 mg/dm^3 to 35.9 mg/dm^3. The team used the least reactive dye found within that literature in order to have the highest concentration of PACl for the experiment. Thus the team considered red DB-8 dye for future experiments.

A few tests were conducted using red dye through the system. However, the dye did not appear to adsorb to PACl. Instead, the dye diffused into both the water and the flocs, causing the entire reactor to appear red. This is illustrated in Figure 14. Because the PACl was not able to adequately adsorb the dye, the red dye was found to not be an adequate tracer for the apparatus.

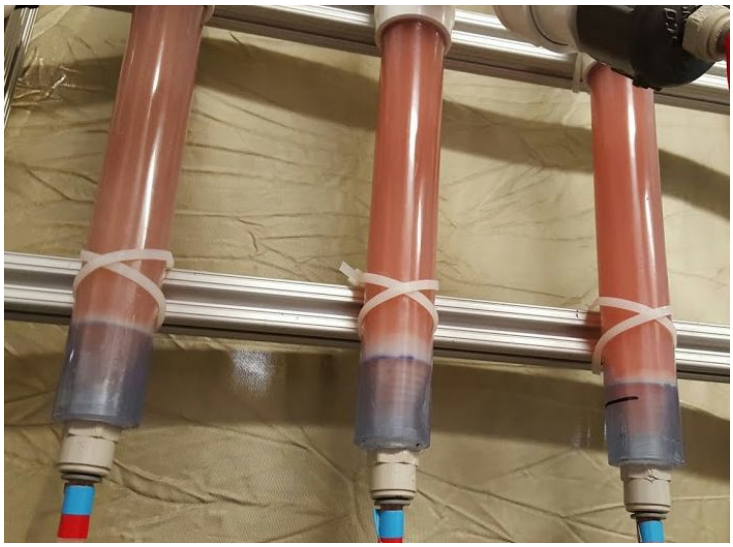

Figure 14: The diffusion of the red dye spread throughout the entire reactor. Thus, the results of floc formation and removal were inconclusive.

Blue Dye

The team looked into alternative types of dye that would be better tracers for the system. In one article, Remazol Brilliant Blue Dye (RBBD) was a species found to be adsorbed by PACl [8]. In the literature, 0.100 g dye was dissolved in the 1 L of tap water and optimum doses (0.025 g to 0.050g) of PACl was given for the adsorption of the dye during a jar test. The concentration of dye in effluent samples were calculated from at λ_{max} of dye = 663 nm. In another published article, the same species of dye was assessed. This literature found the maximum and minimum dye removal efficiencies of RBBD to be 71.7% ± 13.6 and 57.7% ± 34.3 when mixed with PACl [9]. From these two articles, the team is looking to purchase RBBD and test the effective adsorbance of the dye with PACl.

After purchasing the blue dye, the team had to create a new setup with the spectrophotometer.In previous tests the team used a red tracer dye. Therefore, the original LED light used in the spectrophotometer was blue. However, because the team switched to blue dye, the LED light had to be switched to red in order to obtain reliable data for the blue absorbance (a wavelength around 630 nm was required). Once the LED light was implemented, the team created calibrations for the blue dye. The concentrations were 80, 40, 20, 10, and 5 mg/L. Once the calibration data was obtained, the team began testing the dye.

Prior to running experiments using the dye, the team reviewed the MSDS for Remazol Brilliant Blue R and noted from Section 12, Ecological Information, that it should not be emptied into drains. The team contacted Cornell University Environmental Health & Safety requesting permission and instruction to use the dye. EH&S permitted the team to use the dye if the concentration of the dye in the effluent was less than .01 g/mL. The team determined that it would be within this limit and proceeded to begin experiments using the dye.

The stock concentration of dye was 500 mg/L. initially, when the feed entered Reactor 1, thin streams of blue dye were observed. The dye did not overall diffuse throughout the reactor immediately. Instead, the color was first concentrated within the floc blankets. As this happened, the water within top section of the reactor (where the floc blanket was not present) remained clear. Initial results are depicted within Figures 15 and 16.

Figure 15 (Left): The initial result after introducing the reactor with the dye feedstock. The blue dye was concentrated within the floc blanket

Figure 16 (Right): While the initial result in Figure 15 was occurring within the floc blanket, the top part of Reactor 1 remained relatively clear of blue dye.

However, after a short amount of time, the blue dye left the concentrated floc blanket region and began to enter the rest of the reactor. This process of the dye first saturating the floc blanket and then seeping into the rest of the reactor was observed for all the reactors. The final result was a series of three reactors that all appeared saturated with the blue dye (Figure 17). A graph

is also provided, which shows the concentration of dye in the effluent consistently increase, until the extra PACl was added to reactor 3 at 6 pm. Unfortunately, the bottle that contained the extra PACl fell and created the disturbance at the end of the graph.

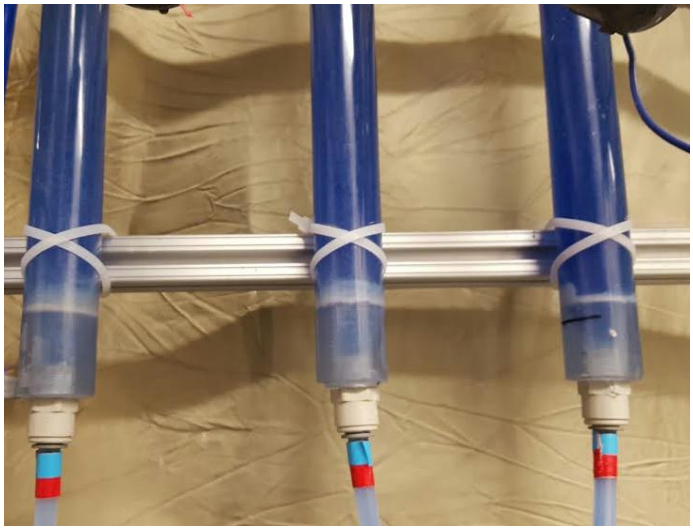

Figure 17: The dye appeared saturated in all 3 of the reactors, indicating that the PACl did not effectively adsorb the dye.

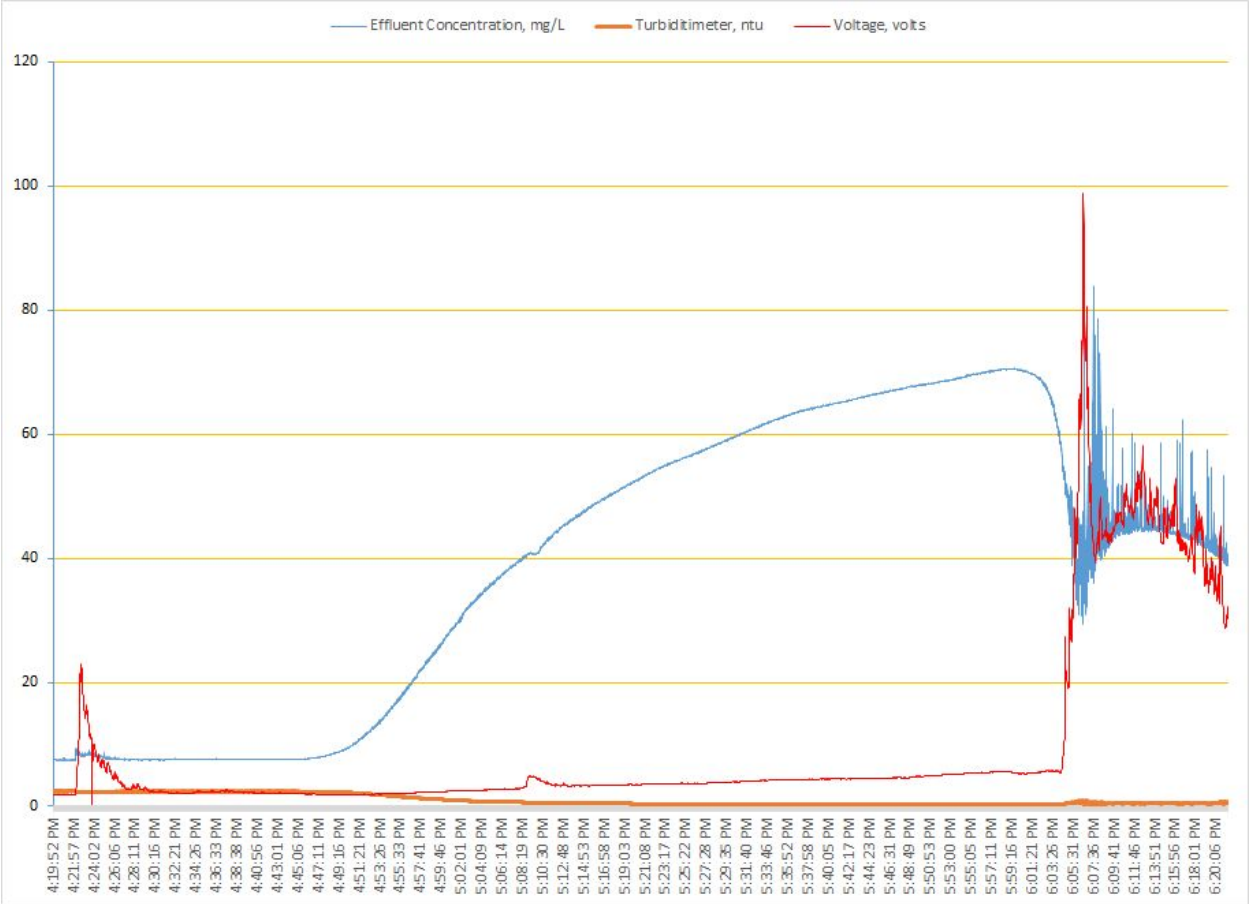

Figure 18: Graph of effluent dye concentration.

The team speculated that the reason the dye was not effectively adsorbed onto the PACl was because the ratio of PACl to dye within the reactor was too low. It was estimated that the concentration of PACl into the reactor was approximately 1 mg/L, compared to the 500 mg/L of dye feeding into the reactor. From literature, effective dye removal occurred when the PACl concentration was approximately 50 mg/L and the dye concentration was 40 mg/L, as illustrated in Figure 19. Thus, the team decided to increase the concentration of PACl inside the reactor. The team created a new inlet, which directly sent 2.6 g/L of PACl into the 3rd reactor. The purpose of this inlet was to maintain the concentration of PACl in the third reactor to enable efficient removal

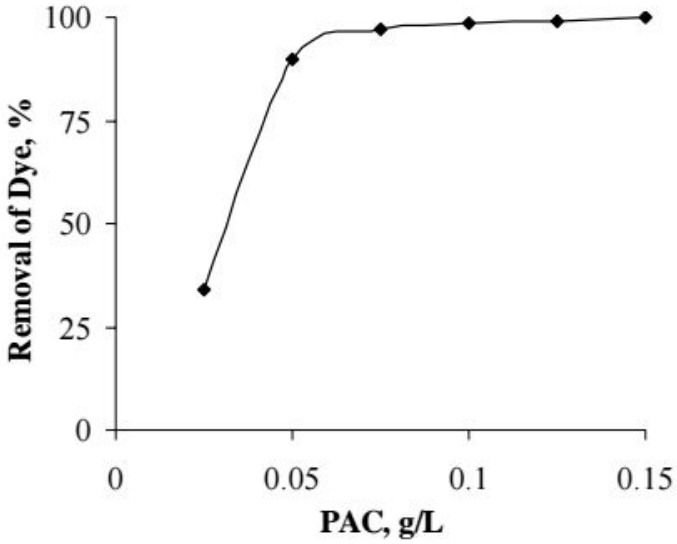

Fig.-5B: The plot of added PAC *vs* dye concentration

Figure 19: The percent removal of blue dye versus the concentration of PACl for a given influent dye concentration of 40 mg/L

of dye and thereby causing a visible reduction in the intensity as reflected by the spectrophotometer. Future tests and observations are planned for the Spring semester of 2016.

Troubleshooting Throughout the Semester

The team encountered several problems while running experiments. Smaller problems included leaks and air bubbles. Leaks were addressed by replacing pipe fittings. Air bubbles trapped within the tubing initially broke up sections of the floc blanket. However, after running the experiment for some time, the air bubbles seemed to all leave the system. Nonetheless, the team is looking into incorporating a mechanism that would allow the air escape prior to entering the reactor.

Another issue was pressure caps at the top of each reactor popping off. This issue occurred while running only water through the setup for the first few times, and it was concluded that the problem existed due to the extremely high flow rate of water. This issue was resolved after moving on to the testing phase, where the flow rate of water was set at the designated (and much smaller) rate. This issue was also noted for future instances of running only water through the system.

In the early testing phase, the reactors did not form floc blankets. The team hypothesized that there was not enough clay concentration with the PACl. Thus, in the next set of experiments, the team increased their clay concentration to approximately 2400 mg/L. With this concentration, the floc blankets were able to develop.

There was also settling observed within the tubing and reactors. Initially, the team was using ⅜ th inch tubing to drain the flocs and pump them into the next reactors. Within these tubes, the flocs were seen to settle at the bottom as the effluent water passed through. This phenomenon was observed in reactor 3 (Figure 20). This hindered the transportation of flocs. To address the problem, the team changed the tubes pumping flocs with ¼ in. tubing. The team also observed the clay and floc mixture settling within the flocculator. Because the flocculator was created with ⅜ in. tubing, the team is looking into replacing those tubes with ¼ in. as well.

Figure 20: An early attempt of forming floc blankets. Due to the low upflow velocity, heavy sedimentation in reactor 3 was observed.

Future Work

The team has several goals for the future. One goal is to close down on variability in order to see the direct effects of changing parameters such as flow rate or concentration. For a future design of the reactors, the team plans to implement shorter floc weirs so that the flocs can be easily extracted as opposed to settling at the bottom of the reactors.

Additionally, the team is looking into testing the effluent floc concentration in each reactor. These tests would then allow a mass balance calculation to determine the amount of flocs filtered out. Thus, the team is looking into using a turbidimeter in order to get the data.

Finally, the team plans to test the RBBD and its adsorbance effectiveness in PACl. If the adsorbance of the blue dye suits the experiment, then the team will modify the spectrometer so that the appropriate blue wavelengths can be picked up.

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