StaRS Filter Theory Team, Fall 2017

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10 December 2017

Abstract

Sand filters have historically been used to lower the turbidity of water, and continue to be used in many conventional water filtration systems. Dynamic modeling, as opposed to static modeling, of rapid stand filtration accounts for the buildup of particles over time in the filter, and this understanding is needed for better filter design and operation. Past sub-teams found that head loss increases linearly with time. This research proposes the hypothesis that flocs are captured in rings created by filter grains, which on a larger scale implies an active filtration zone where empty pores become clogged by the flocs. This active zone moves throughout the bed until there is no remaining space for particles to clog. This research will examine major and minor head loss, along with effluent turbidity, to find optimal filter performance based on varying flow rate, coagulant dosage, and influent turbidity in a 1.967m L/s sand filter. Based on this research, it is hypothesized that the sand bed can filter a certain amount of mass before failing.

Introduction

The goal of the Stacked Rapid Sand (StaRS) Filtration Theory sub-team was to develop a mathematical model to determine the most effective choice of filtration parameters to optimize water filtration for lowest effluent turbidity and longest filtration duration in stacked rapid sand filtration. These parameters included coagulant dosage, flow rate of pretreated water, influent turbidity, and backwash duration.

The sub-team's work-in-progress mathematical and visual model, proposed by the Spring 2017 StaRS Filter Theory sub-team, hypothesize washer-like "dirty" particle build-up within the constricted pores of the sand bed in the stacked rapid sand filter. The influent flow of the in-house built filter apparatus was designed to split and seep through the sand column in both an upwards and downwards direction until all of the pores were clogged. During this process, the effluent turbidity was observed to be improving until filter failure. The filter was said to have failed once the observed effluent turbidity increased.

In an attempt to test the proposed model, experiments were designed to test the effects of varying coagulant dosages on filter performance. Coagulant dosages to influent water were chosen at roughly equal intervals. By systematically varying dosages in subsequent filter runs, the effect of coagulant dose on filter performance and failure time could be determined. Furthermore, experiments were designed to study the effects of shear force between the "dirty" particles and filter medium within the filter by changing the flow rate through the filter. From these studies, a pattern could be found between dosage and optimizing effluent turbidity over time balanced with minimizing the required volume of the filter based on filter parametersfor the given filtration conditions. Previous AguaClara plants have been built with the assumption that sedimentation processes ought to be designed to achieve the highest particle removal possible, leaving small quantities of small floc particles in the effluent water from the sedimentation tanks. However, it was hypothesized that leaving some portion of larger flocs in the influent water by controlling the influent flow rate would allow greater aggregation with the smaller flocs. This aggregation of flocs would create larger clumps of particulate matter that would be easier for the filter medium to capture.

By conducting experiments that test the current mathematical model of the filter through varying influent turbidity, coagulant dose, flow rate, and run time, and determining generalizable principles of the filter physics, the most cost-effective, quality stacked filter can be designed and produced, ultimately helping to make gravity-powered water filtration more affordable and effect to people worldwide.

Literature Review

In their paper, Tien et al. (1979) modeled a sand filter bed using the constricted tube model instead of the classic spherical model where pores within the filter were similar to long straws with a constant width. It was found that the process of filtration can be split into a two step process to be modeled accurately. The first half of the model is based on a clean bed with no particulates attached to the grains. However, as the water was run through the bed, particles began to deposit on the sand grains. Therefore, the second stage of this model sought to account for particle deposition and the deposition changes over time, under the assumption that particles coat sand grains uniformly. The model described how over time, the particulates attaching to the grains increased the volume of solids within the filter. In turn, porosity within the sand bed decreased. From these hypotheses, the model was created using new methods of calculating filter coefficients to predict its complex behavior over time in a sand bed filter.

Previously, the pores permeating granular porous media beds were modeled as capillaries. This model neglected the curvature of the individual grains from the media on particle capture within the sand bed. The omission of this pore characteristic in the modeling of pore morphology in the bed caused major inaccuracies in modeling the shape of the flow of liquid through the filter medium and the deposition of particulates in the bed that the proposed model addresses. While the modeling pores in the filter bed with the constricted tube model was still an oversimplification of the true shape of the sand bed pores, it did so to a lesser degree (Tien et al., 1979).

Previous mathematical models proposed by Tien et al. (1979) for the deposition of particles in a porous bed were governed by the aforementioned constants. First, a distribution of the lengths of periodicity, physically represented by the distance between single grains in the bed, was determined by first simplifying the grains into cubes of average volume, comparing the average volumes of grains with different diameters, and reverting back to a spherical model for the grain. Second, the constriction size distribution, represented by the minimum length between the grains, can be determined from comparing the saturation to the capillary pore sized curve established by Millington and Quirk (1959). Third, the dimensions of a unit cell of the model were determined using the previously defined constants. Fourth, the number of constrictions per unit cross section in the bed was determined using a theoretical frequency distribution function of diameters of randomly packed spheres. However, given the simplistic nature of the model, these values were found to be several orders of magnitudes less than what was determined during experiments (Millington and Quirk, 1959).

The constricted tube model proposed by Payatakes et al. (1973) sought to account for the effect of neighboring grains; the curvature effect of round, granular media; and the constriction and expansion of the flow channel to account for differences between observed filter constants and theorized constants determined by the previous model. In the new model, the capillaries were modified to become rougher, with the curvature of the grains emphasized such that they would have an effect on the deposition of particulates and the flow of the liquid. In experimental results, the observed constants were much closer to theory than the calculated constants.

The model proposed by the Spring 2017 StaRS filter theory team aims to combine the information from previous sand bed research and results from experiments run to propose what is happening on a molecular level in the bed through looking at factors such as turbidity and head loss.

Previous Work

The visual model of constrictions found between the sand grains in the filter was developed from the conclusions of several experimental runs until system failure. System failure within the filter system was defined as the point in time that the filter stopped cleaning the water - as determined when the recorded effluent turbidity of the water was effectively the same as that for the influent. Between filter failure and filter start-up, the effluent turbidity was recorded every 5 seconds and analyzed graphically. During these tests, the head losses of the influent and effluent were also recorded.

Previous Experimentation/Conclusions

The Fall 2016 StaRS filter theory team attempted to examine the effect of varying coagulant mass on the filter's effluent turbidity, head loss, and failure time. To do this, experiments with 5 NTU influent water and varying PACl dosages were performed. The observations were then consolidated graphically to determine possible correlations (Theresa Chu et al., 2016).

PACl and effluent NTU

Filter performance was tested with varied PACl dosages (0, 0.2, 0.65, 1.1, 1.55, and 2 mg Al/L) by the fall 2016 subteam. Figure 1 contains the effluent turbidity over time for the various PACl doses. The filter failure time was determined to be the point where the effluent turbidity sharply increases. Conclusion: No trend was found in the relationship between effluent turbidity and PACl dosage in successive test runs.

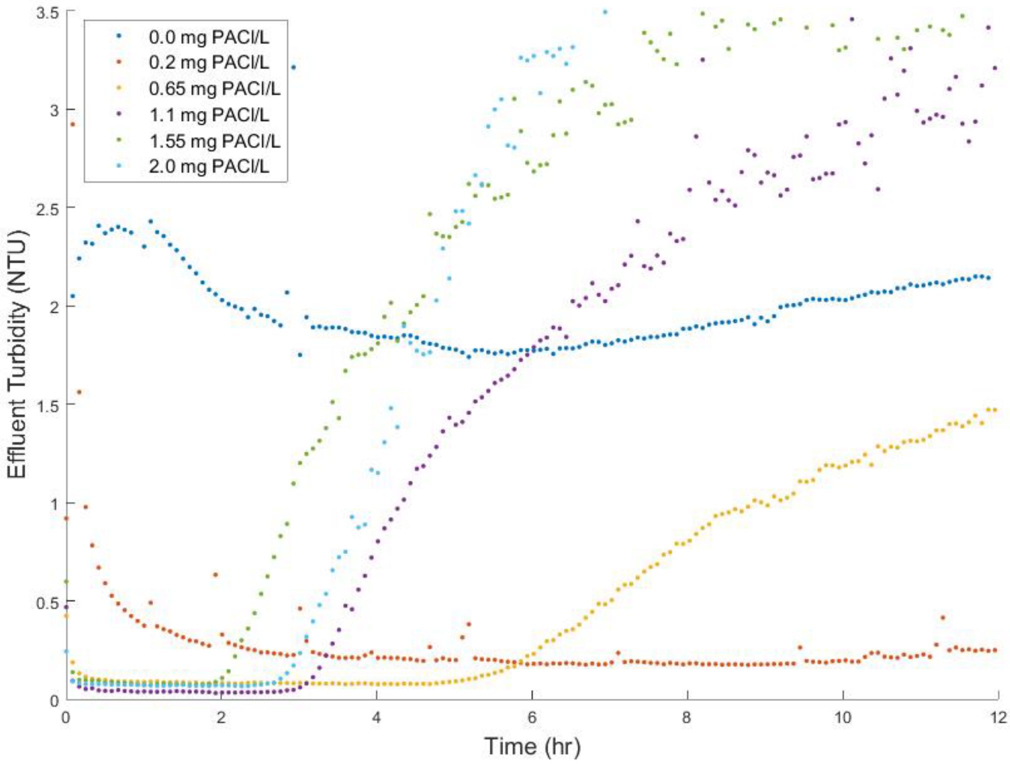

Figure 1: Data detailing observed filter effluent turbidities over time for the six experiments performed with varying PACl concentrations (0, 0.2, 0.65, 1.1, 1.55, and 2 mg Al/L.)

PACl and head loss

Head loss over time data was collected with varied PACl dosages (0, 0.2, 0.65, 1.1, 1.55, and 2 mg Al/L). Figure 2 shows the data for head loss over the same experiments as above. Conclusion: The head loss data demonstrated a relative linear increase in head loss until filter failure time regardless of the concentration of PACl entering the system as seen in Figure 4. This indicates that particles deposit at a constant rate during this time. After filter failure time, shown on Figure 1, the rate of head loss increase appears to slow down.

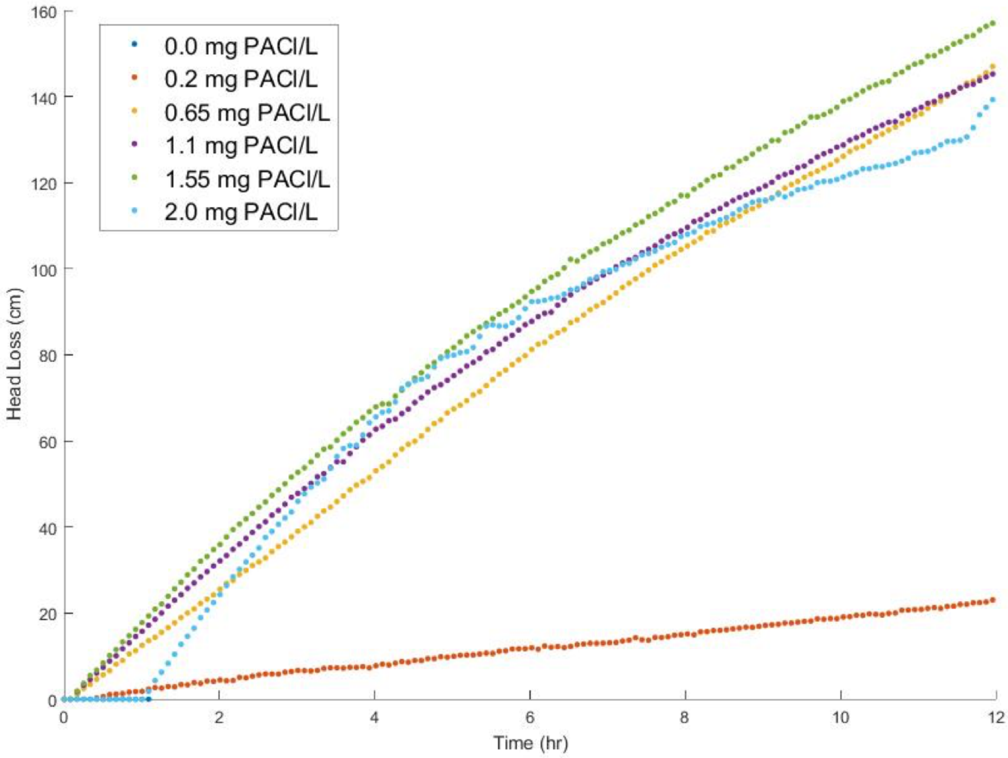

Figure 2: Figure 2: data detailing observed filter head loss over time for the six experiments performed with varying PACl concentrations (0, 0.2, 0.65, 1.1, 1.55, and 2 mg Al/L).

Head loss and velocity

Head loss was measured as a function of filtration approach velocity to determine whether head loss through the filter was due to major or minor losses. The experiment was conducted for a clean bed and for a bed that had filtered 5 NTU water with 2 mg Al/L PACl for 2.4 hours. Figure 2 shows the head loss based on velocity for a clean filter bed. Figure 3 shows the head loss after filter failure in relation to approach velocity after filter failure time. Conclusion: Results showed that the head loss with velocity in the clean bed filter and increased non-linearly with velocity in the clogged filter, as shown in Figure 3 and Figure 4. This indicated that both major and minor losses were prevalent in the dirty bed, while only major losses were prevalent in the clean bed filter. The existence of minor losses in the clogged filter was an indication that the particle deposition caused flow constrictions in the pores, which resulted in flow expansions. Previous teams thus concluded that modeling based on the filtration constriction model would be the most accurate in representing real deposition in the filter.

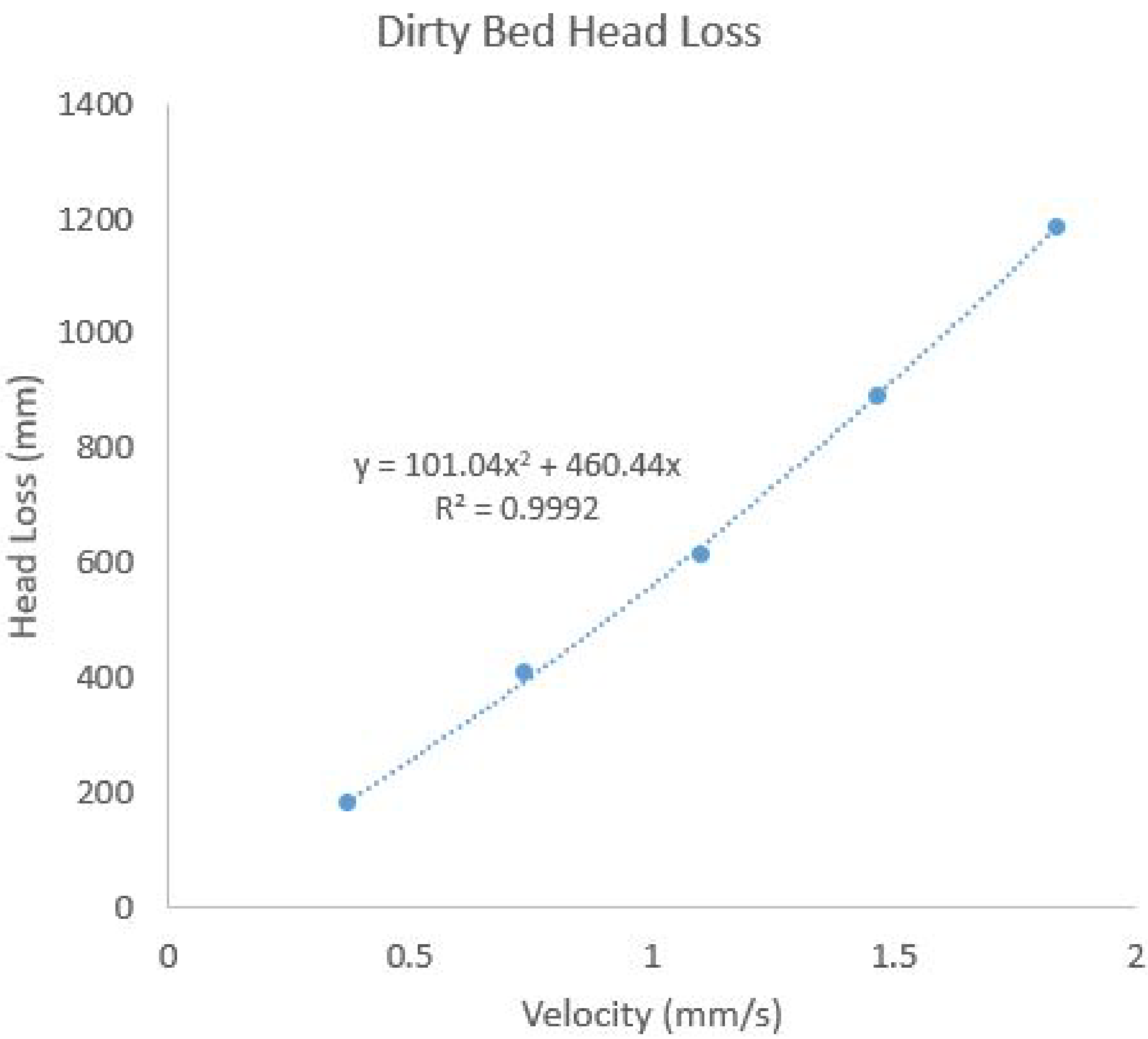

Figure 3: Figure 3: data detailing observed filter head loss per changes to the influent velocity of dirty water into the filter for the six experiments performed with varying influent velocity (0.395, 0.788, 1.574, 1.181, 1.967) after filter failure

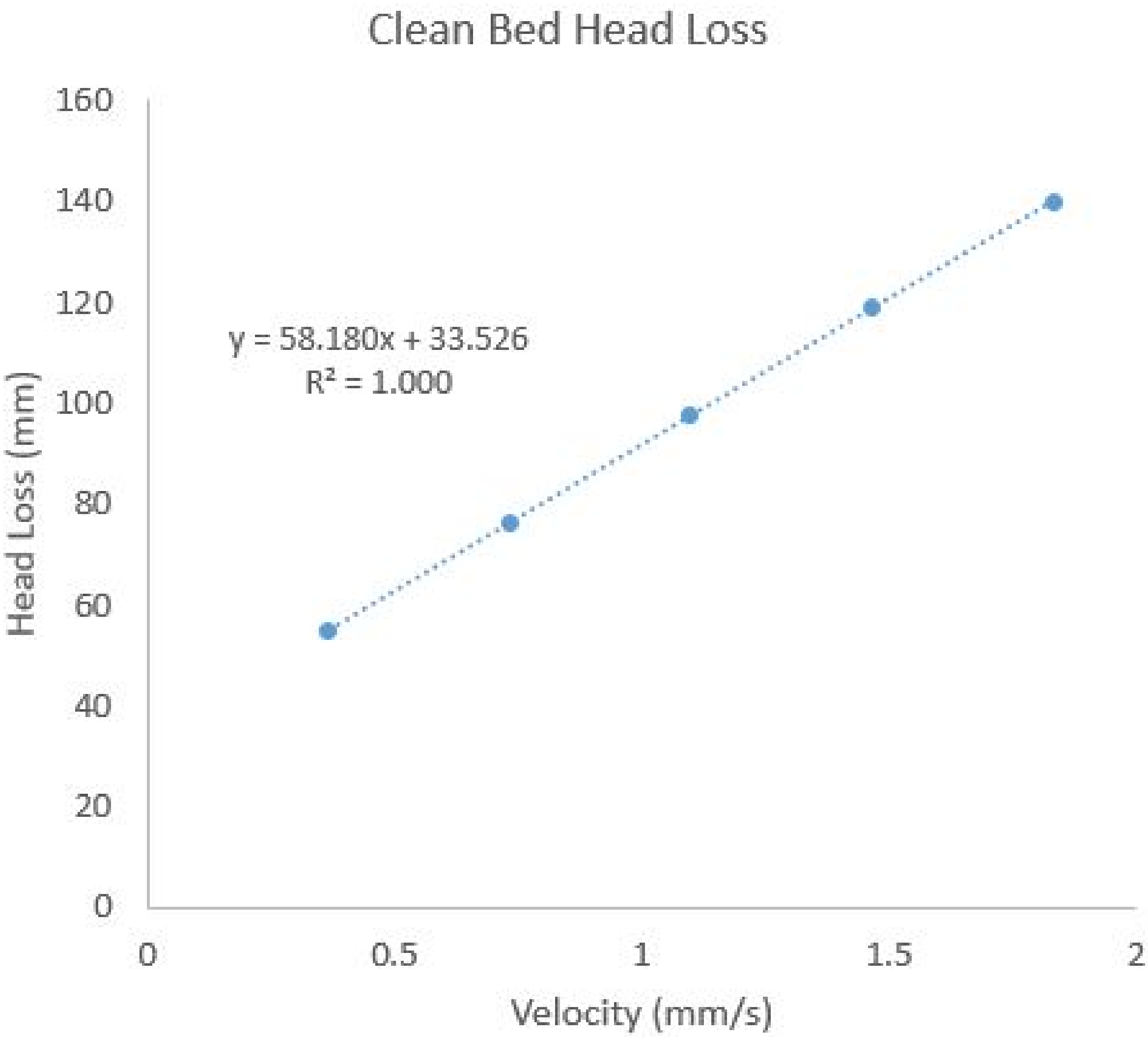

Figure 4: Figure 4:data detailing observed filter head loss per changes to the influent velocity of dirty water into the filter for the six experiments performed with varying influent velocity (0.395, 0.788, 1.574, 1.181, 1.967) before filter failure

Visual Model of Sand Grain Constrictions

From these experiments, two conclusions were reached. First, the minor losses determined from the head loss observations were hypothesized to be due to the constriction and expansion of the flow pathways in a clogged filter. Second, it was determined from the recorded NTU data that the effluent turbidity slightly decreased during the experiment.

A mathematical model was developed to predict the relative size of the pores within the sand grain bed based on the sand grains and packing in the filter system. From this point, various hypothesized models for which the particles built up within the pores were developed and tested to determine if the resulting failure time matched that of the experiments. Other factors were considered in these calculations such as the shear force on the particles due to the velocity of the flow and the affinity of the particles for the sand grains with the addition of the coagulant. From these calculations, it was determined that the closest of the proposed models to fit the parameters of the test was a hollow, cylindrical formation at the narrowest point (constriction) between adjacent sand grains forming a pore for the build-up of the particles, with the constriction of the cylinder growing to a certain critical diameter over time. This work was compiled in a journal article (in preparation) by the Spring 2017 StaRS team.

Methods

Experimental Apparatus

The laboratory stacked rapid sand filter was created with a 65cm length of PVC filled withsand with a diameter of 0.5 mm to 0.595 mm to a height of 40cm. There is one influent pipe and two effluent pipes, all with a diameter of 9.4 mm and made from copper. A schematic of full system can be seen below in Figure 4.

Tap water was pumped into the system and combined with clay and humic acid based on the concentrations calculated by the MatLAB file. The contaminated water stream then entered the influent turbidimeter before going to the contact chamber, where the contaminated water is mixed with Polyaluminium Chloride (PACl), essentially making the clay particles sticky. After leaving the contact chamber, the wastewater entered the flocculator, a helical coil made out of flexible tubing with a diameter of 0.625 mm. The flocculator was designed to increase collisions between clay particles to create flocs that could then be more easily removed in the stacked rapid sand filter. The flocculator was designed with a residence time of 2.67 s for a flow rate of 1.98 mL/s. The energy dissipation rate was 0.27 W/kg, which kept flocs small to simulate influent water for filtration.

Once the water exits the flocculator, it is injected into the stacked filter at an average velocity of 1.8 mm/s. The residence time in the filter was 43.6 seconds on average, after which the water exits the filter through one of the effluent pipes. The two effluents mix and then go into the effluent turbidimeter to measure the turbidity of the water. The difference in turbidity between the influent and effluent water can be used to determine the overall effectiveness of the filter. There is also a 200 kPA pressure sensor immediately before the water enters the filter, and immediately after the two effluent pipes combine in order to measure the head loss caused by the rapid filtration.

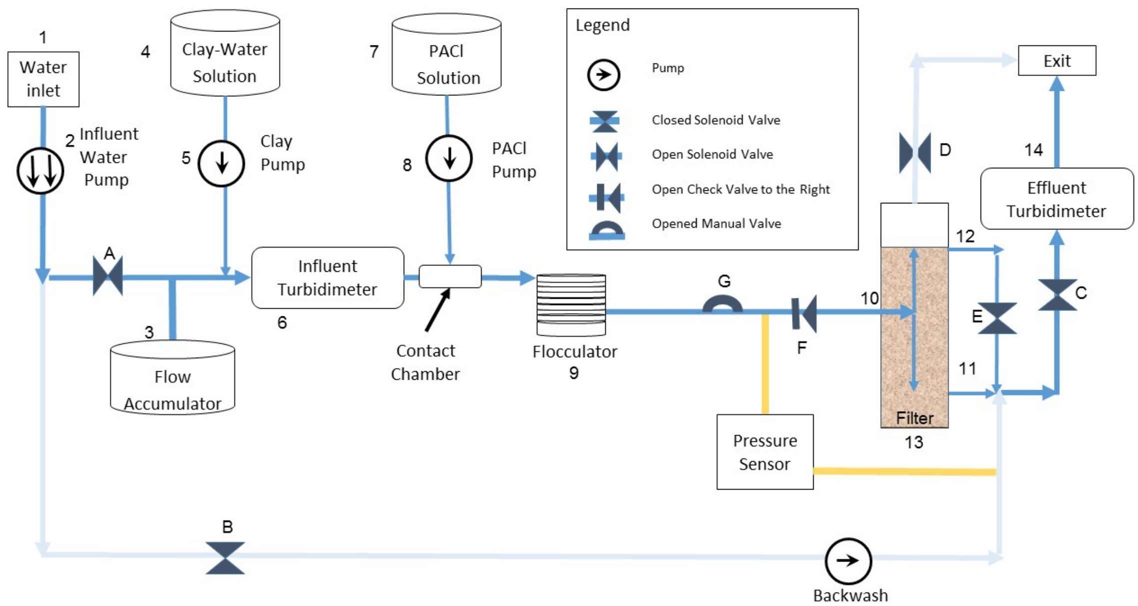

Figure 5: Schematic for the experimental filter apparatus in filter mode showing influent and effluent turbidimeter sampling systems, PACl solution and clay, humic acid solution dosing, pressure sensor to measure filter head loss, and flocculator. Blue connections are used in filter mode. Gray connections are used in backwash mode.

Procedure

Two sets of experiments were run. The first set was to test the consistency of the filter performance between identical runs, and the second set was to test the influence of PACl dosage on filter performance.

For both experiments, there was a constant influent turbidity of 5 NTU and a run time of 12 hours to record the head loss, effluent turbidity and failure time data. The latest edition of the procedural manual was followed in each experiment, including cleaning and backwash procedures. In the first set of experiments, the PACl dosage was held constant at 2mg/L and the concentration of clay and humic acid were consistent. The experiments were run for 12 hours and the failure time was recorded. After the first two experiments, it was seen that the failure time was not consistent in the filter, so the team implemented a rigid cleaning and backwash procedure that resulted in consistent failure time under the given parameters. In the second set of experiments, the PACl dosage was first decreased from 2 mg/L to 0 mg/L in regular increments between each run, and then it was increased from 0 mg/L to 2 mg/L. The data were compared to the results from experiments run in Fall of 2016.

Results

Results

The first set of tests had a 1.967 mL/s influent flow rate and 2 mg/L PACl dosage, and 5 NTU influent water turbidity. Various changes were made to cleaning and backwash procedures to prevent inconsistencies in filter failure time seen in these tests. Figure 6 shows the filter failure time for each of the experiments run under the given parameters. The first two experiments had a large difference in filter failure time, shown in yellow and dark blue, with failure times of 2.78 and 1.79 hours. After implementing a more rigid cleaning procedure, the failure time for the next three experiments were 1.38, 1.38, and 1.74 hours respectively. Figure 7 shows that head loss follows the same patterns for all experiments performed.

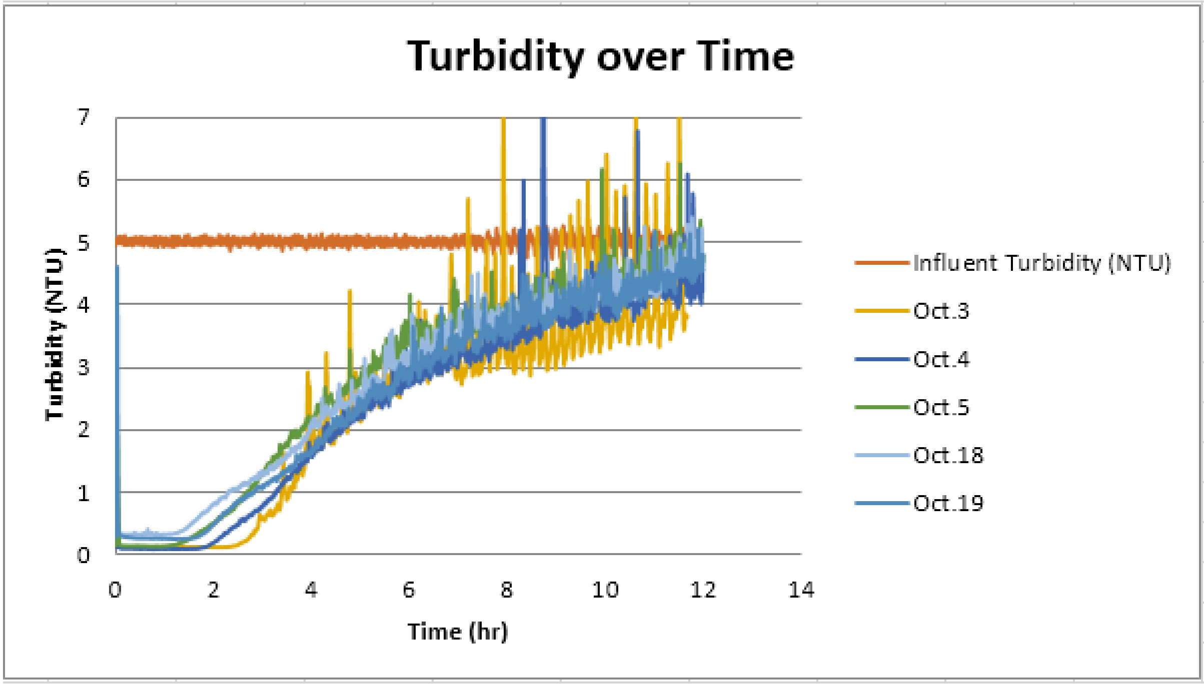

Figure 6: Filter failure time varied between experiments. From Oct.3 to Oct.19 the failure time was 2.78, 1.79, 1.38, 1.38, 1.74 hours, respectively.

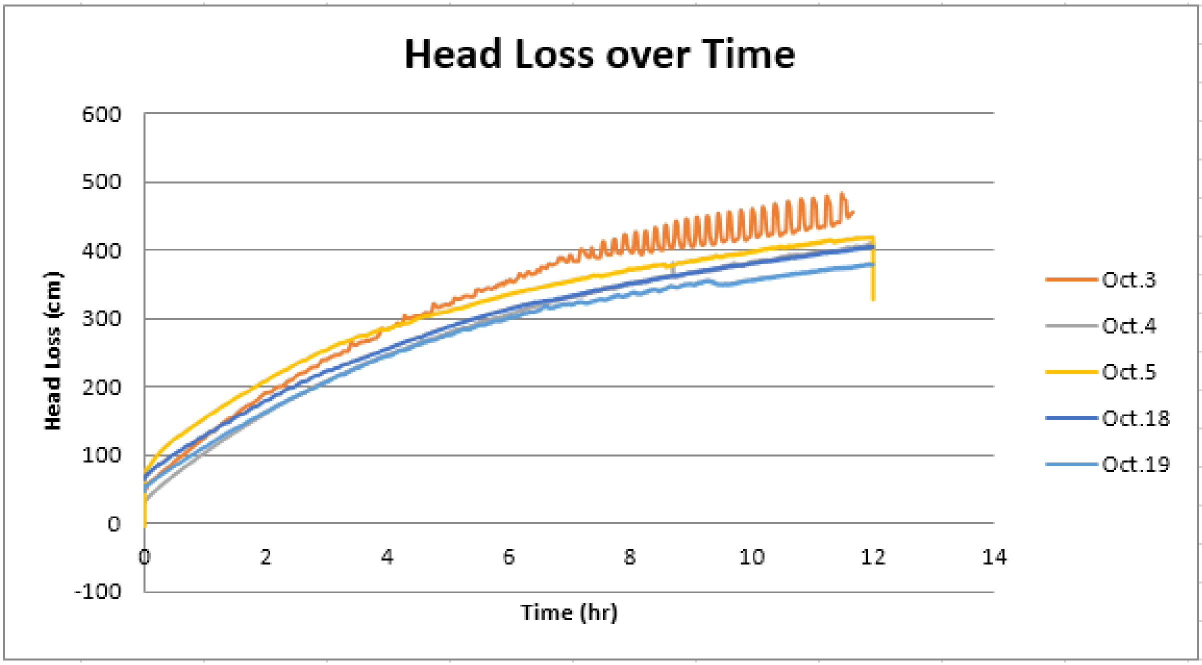

Figure 7: It was observed that the filter head loss increased during each experiment. This was observed in all experiments performed.

The second set of tests had a flow rate 1.967mL/sec and an influent turbidity of 5NTU. The tests were performed using varying PACl dosages of 0, 0.2, 0.65, 1.1, 1.55, and 2 mg/L. Figure 8 shows that before filter failure, the varying PACl doses had varying effluent turbidity. This implies that the PACl doses are having an effect on the amount of mass captured in the filter.

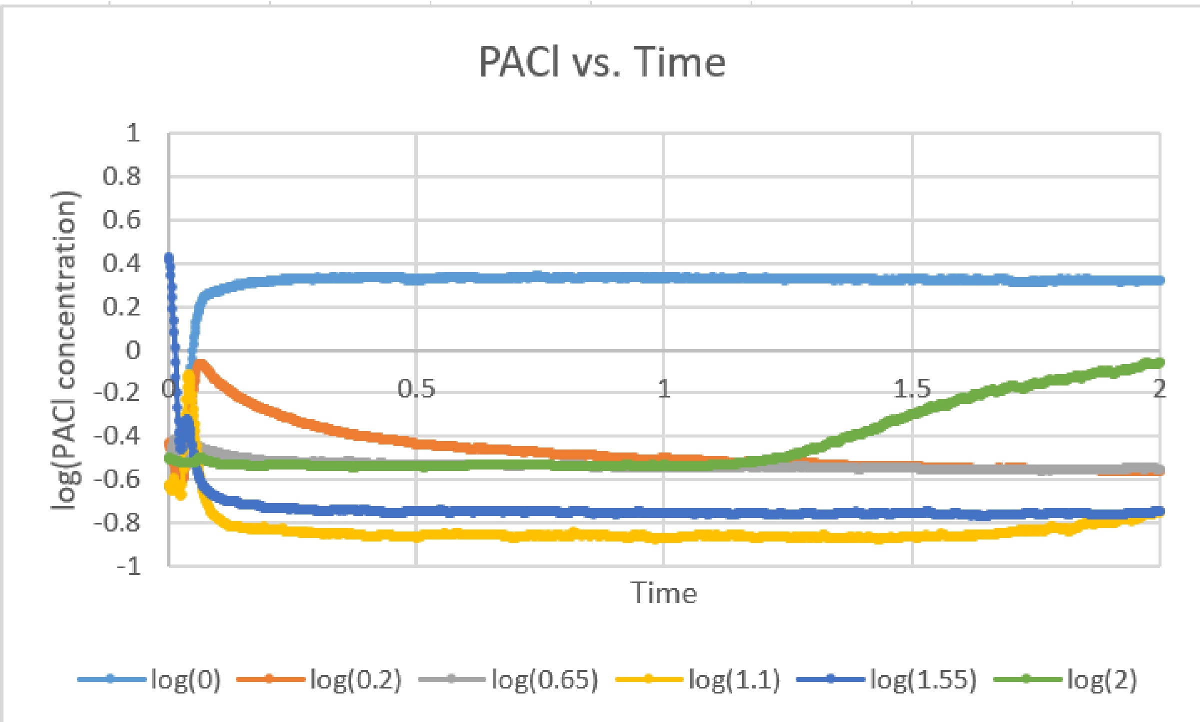

Figure 8: There are varying effluent turbidities before filter failure based on different PACl dosages, suggesting that PACl dose affects how many particles are collected in the filter

From these two experiments, two sets of data were collected from ProCoDA. The first of which was the time of filter failure. This observation was defined by the team as the time at which the observed effluent turbidity of the filter began to diverge towards 5 NTU and beyond. These data were compiled and displayed on a graph depicting the filter failure time (hours) as the dependent variable and the added PACl dosage as the independent variable. The data can be seen in the figure below.

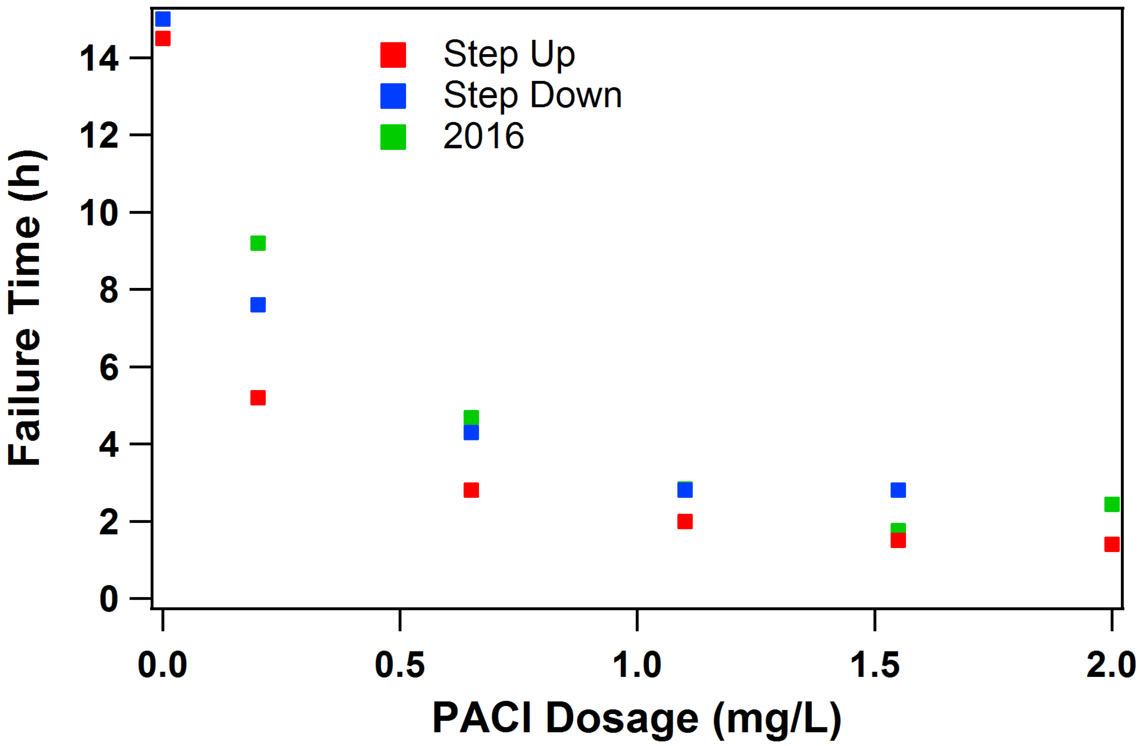

Figure 9: Filter failure times for the performed experiments were plotted against PACl dosage. The data from the 2016 sub-team was also included in this graphic.

Furthermore, the effluent turbidity before filter failure time was recorded during the experiments performed. This observation was defined by the team as the turbidity of the effluent water immediately prior to the divergence in effluent turbidity described earlier. This data was compiled and displayed on a graph depicting the effluent turbidity (NTU) as the dependent variable and the added PACl dosage as the independent variable. The data can be shown in the figure below.

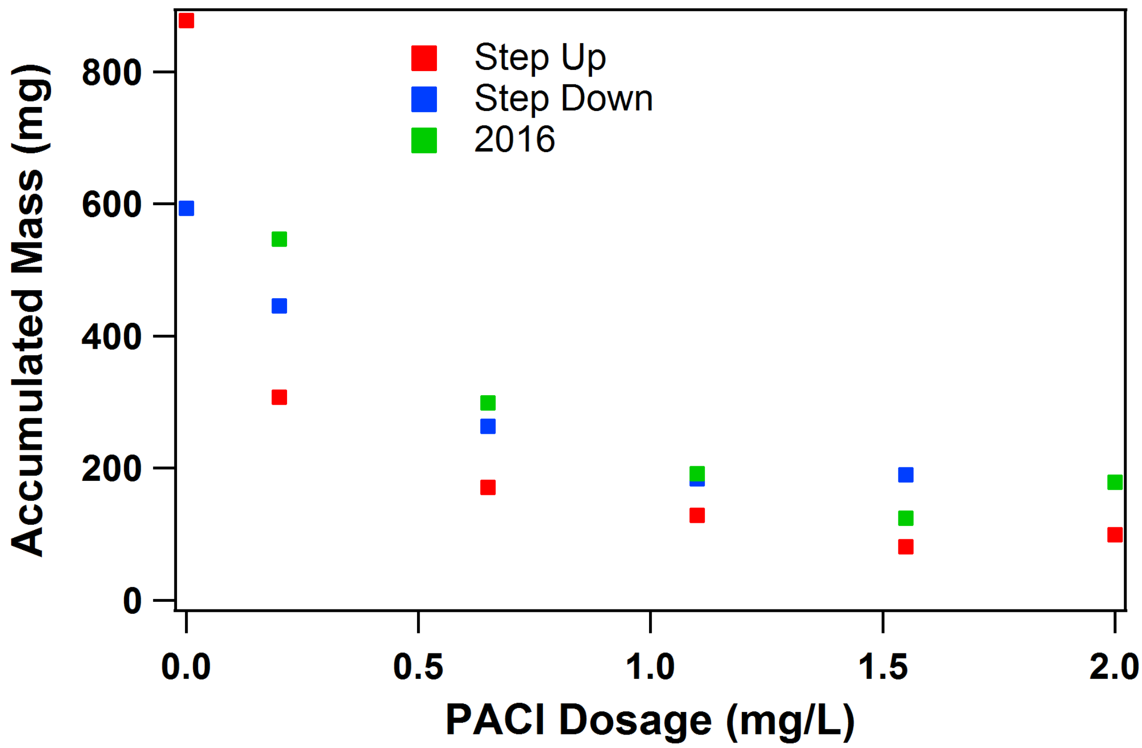

Figure 10: Effluent turbidities before filter failure for the performed experiments were plotted against PACl dosage. The data from the 2016 sub-team was also included in this graphic.

Analysis

While the first set of experiments were run with the same parameters, backwash time was increased to 20 minutes for the last three. It was assumed 20 minutes of back wash would be long enough to ensure consistent filter conditions for each experiment. However, inconsistencies still existed in the subsequent tests. The following list contains other factors that could explain the inconsistencies:

- Variations in temperature: This external factor could cause changes to the physical properties of the experiment's reagents, such as the viscosity of the stock solutions, which would ultimately alter expected head loss through the filter.
- Variations in sand packing in the sand bed: This can change how the bed as a whole captures clay particles, and thus, the bed's effectiveness in capturing the particles. Although, the team agreed that this may be a weaker hypothesis as the sand bed should be packed with enough randomness that the properties of the pores should average out.
- Uncalibrated pumps: The pumps were calibrated and steps were taken such that the team began to check the pump's calibration every two-weeks.
- Settling flocs in cuvette for turbidimeter: This effect could cause inaccuracies and variations in the effluent turbidity reading, which is one of the key observations in determining filter failure time and filter performance.

Based on the experiments run with varying PACl dosages after the procedure was changed to ensure consistency in the filter, it is known that higher PACl dosages lead to lower overall particulates leaving the filter, implying more mass is left in the filter itself. Because of this, it is hypothesized that the filter can hold a certain amount of mass before failure.

Additionally, filter runs were performed to determine the filter failure time and effluent turbidity before filter failure at varying concentrations of coagulant (PACl). In all cases, it seems as though the failure time followed a decaying exponential model. However, an oddity existed regarding the inverse relationship between the PACl Dosage and the failure time. It should be expected that the higher the added PACl concentration, the longer the filter takes to fail: the coagulant makes the added clay "sticky" and as such, the more coagulant added, the stickier the clay should be. This should thus increase the probability that the clay gets caught in the sand bed. On the contrary, data suggested that this was not true. The lower the coagulant dosage, the higher the filter failure time. This result was seen in three different experiments, and should lead to a reevaluation of theory, and a reconsideration of the physics dictating the system. The team brainstormed two possible theories to explain this phenomenon. First, overdosing PACl into the system could cause complete PACl coverage of the clay particles. And, although PACl easily aggregates other particles into larger flocs, it is less likely to aggregate with other particles if the collision is PACl to PACl. Thus, there is potential for some PACl-covered clay particles to slip past the sand bed and contribute to a premature filter failure time. Second, there may exist a limiting quantity of mass or volume that the filter can accumulate before it necessarily fails. In this case, higher coagulant dosages would lead to a larger quantity of clay particles captured in the sand bed in a shorter period of time from the beginning of the experiment. As such, the filter should fail sooner per larger dosages of PACl to the influent water. Further experimentation and modeling needs to be performed to determine the validity of these theories.

Filter runs were performed to determine the effluent turbidity before failure at varying concentrations of coagulant (PACl). In all cases, it is questionable whether there is any relationship between the effluent turbidity and PACl concentration. One could theorize that the lower the PACl concentration, the greater the effluent turbidity before failure. Decreasing the PACl concentration would allow more clay particles to "slip" through the sand bed and thus, contribute to the effluent turbidity. However, this was not was observed. The team is unsure of why this was the case, and will continue to brainstorm explanations.

Mass accumulated in the filter equals the mass going into the filter which is the mass of PACl, clay and humid acid (calculated using the influent turbidity data) minus the mass coming out of the filter(calculated using the effluent turbidity data).

$$M = ((C_{PACl} * Q_{filter} + Turbidity_{influent} * Q_{filter}) - (Turbidity_{effluent} * Q_{filter})) * Failuretime \quad (1)$$

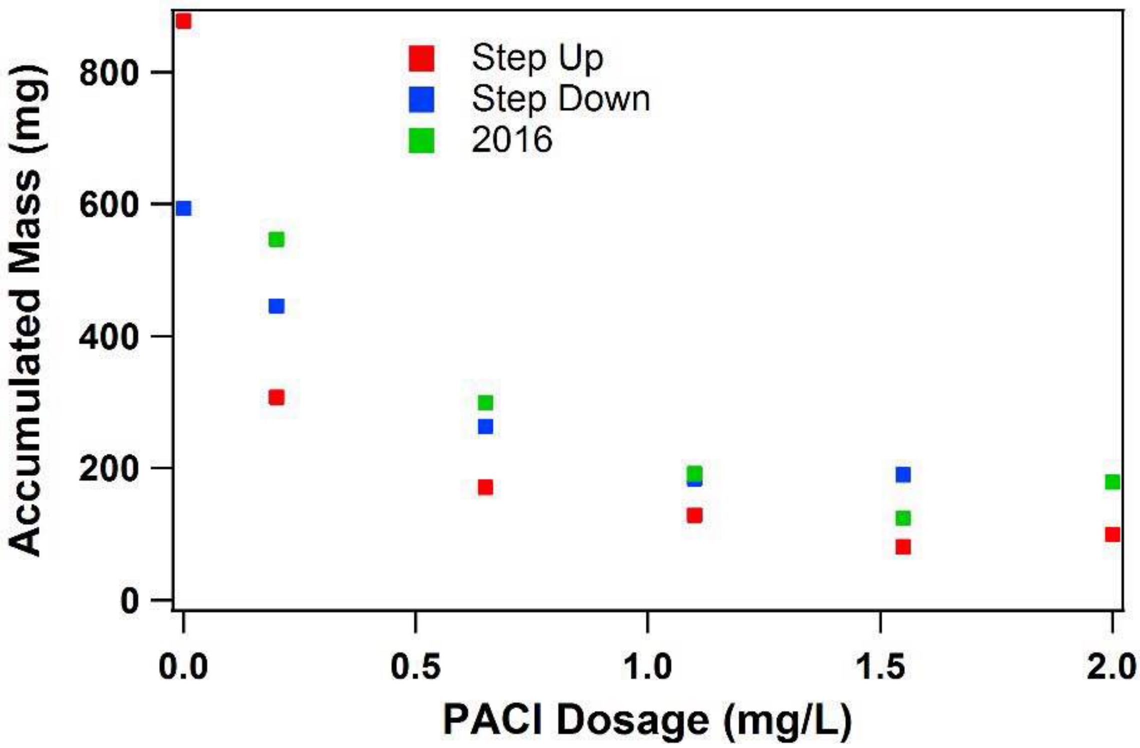

Figure 11: Figure 9 : Total accumulated mass decreases as PACl dosage increases.

As PACl dosage increases, the standardized accumulated mass is supposed to increase, but since higher PACl dosages lead to shorter failure time, the total accumulated mass would decrease. This suggests that with lower PACl dosages, we can hold higher amount of mass before failure time.

Conclusions

The beginning of the semester was plagued by inconsistencies in observed filter failure times, despite constant operational parameters. This prevented the team from moving forward with planned experimentation. This issue was eventually resolved by a reevaluation of previously established, pretreatment procedures. It was determined that filter set-up before filter runs was not thorough enough, and the required five minutes of backwashing was insufficient. The team thus determined a pretreatment procedure that largely solved the observed inconsistencies.

During this time, the team concluded that the observed data from previous teams could not be taken as reliable. Experiments previously performed must be repeated to determine the validity of the results. As such, two rounds of experiments were performed, which mirrored those performed during previous semesters.

The data compiled from the experiments performed by the team followed the same general trends as those found by previous iterations of the teams; albeit, the data were an order or magnitude or so different. As such, the trends found by the team were taken as valid. Even so, the trends did not make much intuitive sense.

As such, the conclusions drawn by the team were less so concrete. The team settled on questions to guide further understanding of the system and theories to provide context to the observed trends. Firstly, the team must conclude upon a theory that would describe the inversely proportional relationship between filter failure time and PACl concentration, and account for the non-relationship between effluent turbidity and PACl dosage. Furthermore, it was determined that further testing and analysis of the mass accumulated in the filter must be carried out in order to optimize PACl dosage, as previously described. Lastly, the range of PACl dosages must be reevaluated in accordance to the calculated coverage constant, gamma, to determine whether the relatively arbitrary dosages cover a wide enough range to determine the effect of PACl coverage on the clay particles.

Future Work

Future research will be centered around confirming the hypothesis that the filter can hold a predetermined amount of mass before it fails. By using mass balances and running experiments to confirm the balance, it is hoped that a definitive equation can be found and applied to existing AguaClara Plants to minimize cost of PACl dose and frequency of backwashing while maintaining effluent water quality. Further work can include analyzing particulates entering and exiting the filter to determine if there is a pattern in the particles that escape the filter. Furthermore, by using the gamma value of the interactions between PACl and clay particles, PACl dosage and flocculation design can be used to achieve optimal coverage of clay particles for best filter performance.

References

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Payatakes, A. C., Tien, C., and Turian, R. M. (1973). A new model for granular porous media: Part I. Model formulation. *AIChE Journal*, 19(1):58–67.

Theresa Chu, Jonathan Harris, Lucinda Li, and William Pennock (2016). A Model for Stacked Rapid Sand Filters. AguaClara Subteam Fall 2016, Cornell University, Ithaca, NY.

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Semester Schedule

Task Map

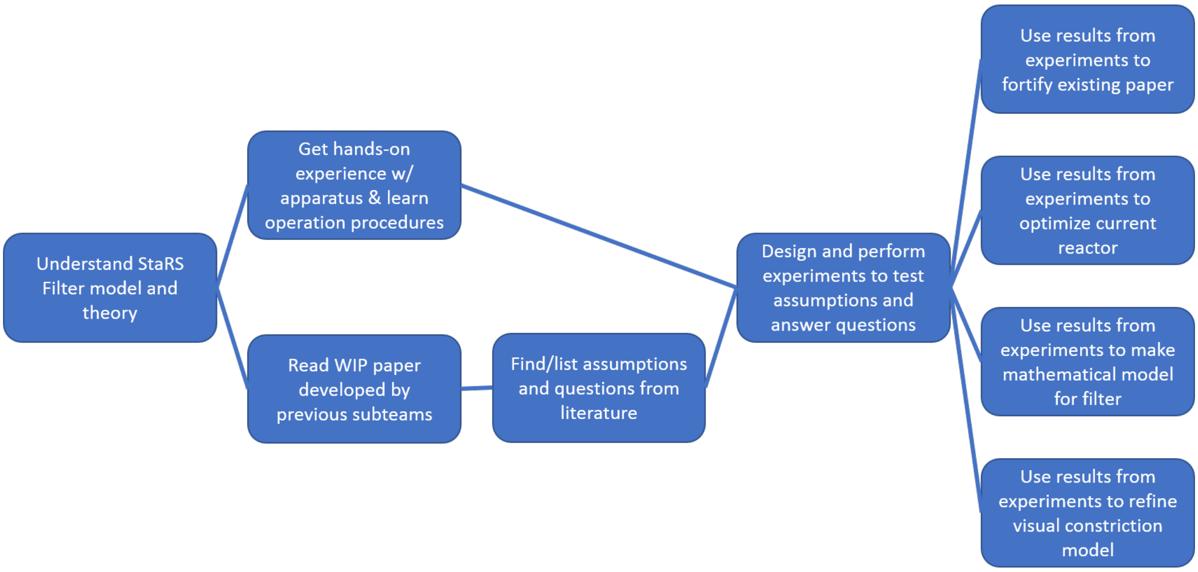

Figure 12: StaRS Filter Theory Fall 2017 Task Map

Task List

1. ✓Understand the model and theory (9/8/2017) - Dylan. The team will finish reading the paper produced by last year's team and other associated literature while listing assumptions and questions that can be tested later on.

2. ✓Operating Apparatus (9/12/2017) - Lingzi. Get hands-on experience with the apparatus and learn how to operate it in the lab.

3. ✓Ensure filter consistency (10/15/2017) - Liz. Determine necessary procedures and conditions to guarantee consistent filter failure time with consistent experimental parameters.

4. ✓Challenge assumptions about optimal PACl dosage (11/15/2017) - Dylan. Conduct experiments with varying PACl dosages to determine optimal dosage that decrease effluent turbidity and maximizes filter failure time.

5. ✓Determine mass that filter can hold (12/1/2017) - Lingzi. Use a mass balance to determine the total mass of clay and PACl the filter can hold before filter failure is reached. Apply this to the existing AguaClara plants to optimize PACl dose and filter failure time.

Manual

Experimental Apparatus

A stacked rapid sand filter was created at the laboratory scale using a column of clear PVC pipe filled with sand. A schematic of the apparatus can be seen in Figure . The PVC pipe had an inner diameter of 2.6 cm and was 65 cm high. Sand sieved from sieve numbers 30 to 35 (0.595 mm to 0.500 mm) was used as the filter media and filled the column to a height of 40 cm. The porosity of the sand was assumed to be 0.4 by the Spring 2017 StaRS filter theory sub-team. The residence time of the filter was 43.6 s. The approach velocity in the filter was 1.8 mm/s and the overall flow rate of the system was 1.98 mL/s.

The inlet and outlet pipes were made of copper pipe with an inner diameter of 9.4 mm. The inlet pipe models an injection system that was made of PVC pipe with closely spaced downward-facing holes. The injection system modeled is made up of PVC pipe with an outer diameter of 3.34 cm (nominal diameter 1") and a 10 cm center-to-center distance between orifices for sand layers that are 20 cm deep. The ratio of the areas of the orifice and filter is equivalent to the ratio of the inlet pipe outer diameter to the spacing between orifices, described by equation 2.

$$\frac{A_{\text{Or}}}{A_{\text{Fi}}} = \frac{OD_{\text{Pipe}}}{B_{\text{Or}}} \tag{2}$$

The resulting area of the orifice for the apparatus's filter was 1.8 cm^2. To maintain this area for the inlet pipe with insufficient surface area for a circular orifice, a rectangular orifice of the inlet pipe was cut with dimensions of 0.80 cm x 2.24 cm. Copper mesh with openings of 0.23 x 0.23 mm and a porosity of 0.3 was welded to the outlet pipes of the filter to prevent unintended media removal.

The coiled tube flocculator was made of clear flexible tubing with an inner diameter of 0.625 mm and a length of 1.32 m. The flocculator was designed with a residence time of 2.67 s for a flow rate of 1.98 mL/s. The energy dissipation rate was 0.27 W/kg, which kept flocs small to simulate influent water for filtration.

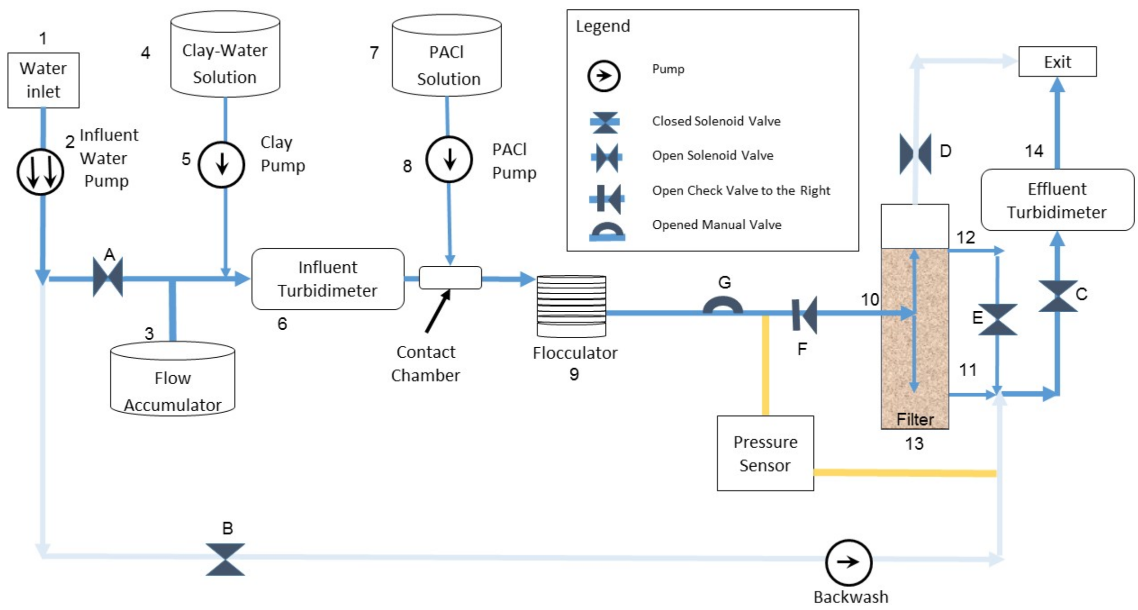

Figure 13: Schematic for the experimental filter apparatus in filter mode showing influent and effluent turbidimeter sampling systems, PACl solution and clay, humic acid solution dosing, pressure sensor to measure filter head loss, and flocculator. Blue connections are used in filter mode. Gray connections are used in backwash mode.

For easy reference to different parts of the apparatus, the different components are categorized in three systems: the influent system, the effluent system, and the backwash system. The influent system refers to the tubing that connects influent water and the PACl and clay stock tanks to the influent turbidimeter and ultimately to the filter inlet. The effluent system refers to tubing connecting the outlet pipes of the filter to the effluent turbidimeter and out of the system. The backwash system refers to the tubing connecting the influent water to the lower outlet pipe of the filter and the tubing out of the top of the filter and out of the system.

The Stacked Rapid Sand Filter apparatus has progressed over past semesters for the current design. The Fall 2013 report describes the original design for the filter column, outlet systems, and the rest of the apparatus. The Fall 2015 describes the flocculator design and the new inlet system with a single orifice.

ProCoDA Methods

States

- Off: All solenoid valves are closed. All pumps are off.
- Filter: Pumps clay-suspended water, PACl, and clean water into the influent system for testing filter performance.
  - Open - solenoid valves A, C, E
  - On - clay pump, PACl pump, influent pump
- Backwash: Removes clay particles from the experimental apparatus.
  - Open - solenoid valves B, D
  - On - influent pump
- Backwash Half Flow: Removes clay particles from the experimental apparatus. Operates at half flow in order to reduce sand rising as a column and to help the sand fluidize earlier.
  - Open - solenoid valves B, D
  - On - influent pump
- Backwash Toggle: Solenoid B is open and closed periodically so that the water pulses through the filter during backwash. Pulsing the water helps the sand fluidize.
  - Open - solenoid valves B, D
  - On - influent pump
- Backwash and Inflow: Water flows through the influent and backwash systems.
  - Open - solenoid valves A, B, C, D
  - On - influent pump
- Open Solenoid Valves: Pre-experimental state opens solenoid valves so that pressure sensor readings between Off and Filter states change minimally.
  - Open - solenoid valves A, C, E
- Calibrate pumps: Turn a pump on for calibration.
  - On - desired pump for calibration.
- Toggle: Tests solenoid valves individually. The setpoint Toggle is used to set a solenoid valve to switch off and on quickly.

Setpoints

- On: This setpoint corresponds to Boolean 1 and is used to turn pumps on and open solenoid valves.
- Off: This setpoint corresponds to Boolean 0 and is used to turn pumps off and close solenoid valves.
- Runtime: This setpoint corresponds to the amount of time a certain state will run until it transitions into the next state (this setpoint is used in automatic mode).

Variables

- Influent/Backwash/PACl Pump Speed: These variables use pump control code. It has inputs of flow rate and mL/revolution. It outputs a pump fraction. This can also be used to calibrate the pumps through setting a desired RPM in Procoda and placing the pump on the same RPM manually.
- Clay Pump Speed: This variable uses Proportional-Integral-Derivative (PID) control code. It has inputs of P, I, D, a target value, and a current value. It outputs a pump speed. P is the proportional term used to compile present values of error. I is the integral term that integrates the past values of error such that the system can detect how much change in the pump speed is needed to acquire the target value. The P and I values used were 500m and 200m, respectively.
- PACl Flow Rate: This variable uses chemical dosing pump speed code. It has inputs of influent flow rate, PACl stock concentration, and PACl dose concentration. It outputs a flow rate, which is used to determine the PACl pump speed.
- Turbidity: This variable uses turbidimeter code. It has an input of turbidimeter ID. It outputs the turbidity reading.

Running an experiment

1. Once every two weeks: Calibrate the water pump by finding the rpm which yields a desired flow rate.
2. Once every two weeks: Calibrate the PAC pump by finding the rpm which yields a desired flow rate.
3. Once a week: Calibrate the clay pump through ProCoDa.
4. Follow cleaning protocol.
5. State: Filter no clay to ensure there are no air bubbles in the system before the filter.
6. Prime PACl pump to get rid of air bubbles in tubing PACl tank to contact chamber.
7. Backwash if there are air bubbles in the filter.
8. State: Filter no clay. Run until effluent turbidity is below 0.5 NTU, indicating that residual clay and coagulant is minimal.
9. State: Off. Ensure the height of the settled bed remains constant between experimental runs, it necessary, externally agitate the filter to settle the bed. Ensure there is no sand stuck a the top of the filer by tapping the pipe with the hammer.
10. Ensure the influent water turbidity is as expected for clean tap water.
11. Ensure the mixer for the clay stock tank is on.
12. Ensure the valves to the bed and the PACl stock tank are open, ensure the lid to the PACl stock tank is unscrewed
13. Ensure that there is enough solution the PACl and clay stock tanks for the experiment run. Instructions for replenishing the stock tanks are below.
14. Ensure the data is going to the proper file on the computer to prevent lost data. It should either be automatically uploaded to Google drive or the data should be manually uploaded after the experiment is completed.
15. State: Open Solenoid Valves. Zero pressure sensor in ProCoDA (Click Volts, click Zero). Turn on the Clay pump.
16. State: Filter. Start a new experiment. Manually set PACl pump speed. Turn on Automatic mode. Turn on the clay pump and the start the PACl pump.
17. Ensure that PID control for the clay pump properly adjusts the influent turbidity to target turbidity.

Replenishing Clay & PACl Stocks
The Clay & PACl stock Mathcad file contains the information necessary for refilling the stock tanks.

1. Set the amount of liters needed for the stock tank
2. Calculate the mass amount necessary for this amount of water.
3. Weigh out the correct amount of clay and humic acid to the thousandths place.
4. Measure the correct amount of tap water in a Volumetric Flask. Use the water to pour any remaining clay or humic acid from the weight balance into the tank.

   For PACl stock tank:

5. Use the deionized water in lab to partially fill a 1L volumetric flask.
6. Pipette the correct volume of PACl needed for 1L of water
7. Fill the rest of the flask with deionized water
8. Repeat the process and refill the stock tank

Cleaning Protocol

A cleaning protocol was formalized so that each filter run started with a clean filter, flocculator, and system tubing. Cleaning involves steps to help sand in the filter fluidize and clean the filter, clean the walls of the tubing, contact chamber, flocculator, and cuvettes for the next filter run . A successful backwash state is when the filter sand fluidizes completely and the system is in the Backwash state continuously without sand clogging the apparatus and preventing water flow, and there is a negligible change in headloss. Vinegar is used in cleaning to reduce the pH of the water and allow the coagulant to dissolve into the water more easily. The state of the system begins in the Off state after a filter run. Only the influent water pump should be on.

1. **Clean filter sand.**
   (a) State: Filter no clay for 1 minute.
   (b) State: Backwash Half Flow. Ensure that the filter bed fluidizes.
   (c) State: Backwash Toggle. Ensure that the filter bed fluidizes at the full flow rate while the solenoid valve controlling influent water for backwash is toggling.
   (d) State: Backwash. Run for 20 minutes, and continue backwashing if there are visible clay particles in the filter. If the filter sand has not yet fluidized, Off, Backwash Half Flow, Backwash Toggle, and Backwash helps break up the sand column.
   (e) State: Off.

2. **Clean contact chamber, flocculator, and tubing from PACl stock tank.**
   (a) Close the manual valve after the flocculator. Disconnect the system at the tubing after the flocculator and before the valve. Turn the clay pump off.
   (b) State: Filter. Place a bucket at the open end of the flocculator to catch influent water.
   (c) Replace the PACl stock tank with a tank of vinegar (5% acidity).
   (d) Run the PACl pump at full speed for 30 s to flush the contact chamber and flocculator with vinegar.
   (e) Replace tank of vinegar with tank of water. Run the PACl pump at full speed for 30 s to remove vinegar from the system.
   (f) State: Off.
   (g) Clean the contact chamber, flocculator, and tubing. Disconnect the system at the tubing before the contact chamber and flush the dirty parts of the system with water.

(h) Reconnect all parts leading up to the filter. Ensure the piece of micro-tubing in the contact chamber is approximately half way in the chamber.

3. Clean turbidimeters

(a) Empty turbidimeter cuvettes and rinse with DI water.

(b) Screw cuvettes back in and wipe outside with a Kimwipe. Do not reassemble turbidimeters yet.

(c) State: Filter No Clay. Ensure that there are no leaks from the cuvettes.

(d) Shake to ensure there are no air bubbles in the system.

(e) State: Off. Reconnect system at flocculator.

(f) If there are no leaks, put the cuvettes back into the turbidimeter. If the turbidimeters are wet, bake the dessicant for an hour at 100deg C.