Stacked Rapid Sand Filter Theory, Spring 2015

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Abstract

The Stacked Rapid Sand Filter Theory team designed and built an apparatus to induce clogging and test the head loss across a slotted pipe, which allows water to flow into the filter without sand leaving the filter. Experiments were run with high turbidity and coagulant dosages to clog the slotted pipe and determine which influent conditions led to clogging and high head loss. Slotted pipes as an injection system for the stacked rapid sand filters have proven to be problematic due to clogging. Results showed that floc build up of coagulant and clay increased head loss and clogged the slots.

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Introduction

The Stacked Rapid Sand (StaRS) Filter is the last process in AguaClara water treatment, after chemical dosing, flocculation, and sedimentation. Flocs, or aggregates of particles, are formed during flocculation. The flocs then settle out during sedimentation. The goal of the StaRS Filter is to remove the particles that were too small to be removed through the previous steps. The StaRS Filter consists of a column of sand with six layers, with four inlet pipes and three outlet pipes on one side of the column. The filter is cleaned through a process called backwashing, in which water, sent up through the bottom of the sand filter, fluidizes the sand column and exits through the top of the filter column.

The StaRS Filter Theory Team hopes to develop a mathematical model that can provide more specific information about the StaRS filter, given a set of design and operating parameters. The goal for this model is to predict the mass of clay accumulated with respect to coagulant dosage concentration before particles can no longer attach to the filter media. The model will also predict pore storage volume and head loss as a function of coagulant dosage. From this model, one would then be able to calculate the theoretical filter run time before failure.

Over time, flocs build up along the sides of the sand pores, decreasing pore diameter and increasing shear force. Eventually, the flocs will be unable to attach to the sides of the sand pores, and dirty water will exit the filter because the flocs have not been removed, a condition known as breakthrough. At this point, the filter has failed. Once the filter fails, it must be backwashed before clean drinking water will be produced again. In order to optimize the water filtration process, the filter should be backwashed at the correct time. If the filter is backwashed too late, after the filter has already failed, dirty water will be distributed to the system. Conversely, if the filter is backwashed too early, the filtration capacity would not have been reached and more clean water would be used to clean the filter before it is necessary. This model will help determine the optimal time to backwash, ensuring water conservation and clean water distribution to the system.

Last semester, data suggested that there was potentially significant head loss across the copper mesh, which is used to model slotted pipes in the filter column model. However, this data was not very consistent. In Honduras, there have been reports of clogging in the slotted pipes due to organic matter, which greatly limited the effectiveness of the stacked rapid sand filters. The slotted pipes were not designed to be cleaned often, since the water entering the pipes was not expected to clog the slots. When clogged, the slotted pipe system has high head loss and prevents water from entering the filter. Water entering the StaRS filters is typically around 5 NTU or lower, so if these turbidity levels cause the slotted pipes to clog, then a different injection system should be implemented. Since high head loss due to the slotted pipes had not been rigorously tested or documented, an experimental apparatus was designed to determine head loss across an actual slotted pipe, instead of a copper mesh model.

If there is substantial head loss across the pipes, a new injection/extraction system will be designed. A possible option for a new injection/extraction system into the filter is an upside-down U-shaped design. The StaRS Theory team plans to work closely with the StaRS FInE team who is hypothesizing ideas for new injection and extraction systems.

Literature Review

AguaClara utilizes sand filtration to provide clean drinking water. In sand filtration, colloids and flocs in the water become trapped between the sand particles, preventing them from exiting the filter. There are two main subsets of sand filtration: slow sand filtration and rapid sand filtration. As could be deduced by its name, slow sand filters purify water which is moving at a slow speed (0.03-.12 mm/s). The sand particles are roughly 0.2 mm in diameter. In slow sand filters, bacteria which live in the sand regulate the amount of pathogens in the water and in this way, provide for cleaner water ("Slow Sand Filtration", 2013).

The other relevant type of sand filtration is rapid sand filtration, which is the basis for the filtration used in the AguaClara plant. In a conventional rapid sand filter, there are 3 layers of media; the top is anthracite, middle is sand, and bottom is gravel. However, in AguaClara sand filters, only sand is utilized. It has been shown that the ratio of the size of smallest to largest grains of sand in a rapid sand filter should be 1.5, to keep the sand size as uniform as possible (Chu, Garcia, & Schwab, 2014). Furthermore the speed of the water entering a rapid sand filter is roughly 0.7-2.8 mm/s, notably faster than in the slow sand filters. In the AguaClara plant, the water enters the rapid sand filter pretreated by coagulation, flocculation, and sedimentation (Weber-Shirk, 2014). It's important to note that water entering rapid sand filters requires pretreatment of these kinds. This is because the rapid sand filters work best when treating water with low NTU. Slow sand filters don't require pretreatment and can handle water of up to 10 NTU turbidity ("Sand Filtration: Rapid vs. Slow", 2004). It's also advisable for the water entering the slow sand filters to have a flow rate of $100L/(hr \bullet m^2)$ ("Slow Sand Filtration", 2013). This is a disadvantage of the slow sand filter because a relatively large top surface area (1 square meter) is required in order to accommodate a typical flow rate of 100 L/hr.

The AguaClara plant uses a Stacked Rapid Sand (StaRS) Filter, an efficient modification of the traditional rapid sand filter. This filter is effective because the stacked version has more layers of sand for filtering, stacked upon themselves, but also uses the same water to backwash all the sand (Chu et al., 2014). Unlike a slow sand filter, the StaRS Filter is efficient because it uses less top surface area but virtually the entire depth of the filter. Also, the backwash is controlled by single valve pumps (Chu et al., 2014). Additionally, the AguaClara plant has six layers of sand in the filter (Weber-Shirk, 2014).

As referenced in the *Introduction* of this report¸ the tests in the Fall 2014 semester were inconclusive as to how much head loss there is as a function of coagulant dosage and turbidity. As a result, a prominent goal of the Spring 2015 StaRS Theory subteam is to determine more consistent head loss measurements. The tests will be done by creating a slotted pipe apparatus to test head loss through the pipe and effluent turbidity with respect to the coagulant dosage and influent turbidity. If there is considerable head loss, it will be asserted that the 0.2 mm slots in the pipe clog and it will be necessary to switch to a different injection system.

Methods

As said before, an experimental apparatus was constructed to test the clogging capacity of the slotted pipes. As seen in Figure 1 (a schematic of the apparatus), influent water is pumped into a ¼” tube leading into an open tank. Before the tank is a flow accumulator, which will be used to maintain a steady flow of water into the tank to prevent pulsing of water. A slotted PVC pipe models the slotted pipes used in AguaClara plants. An overflow pipe to drain the incoming flow sets the water level in the tank, which is above the slotted pipe.

Slotted Pipe Apparatus

The diagram in Figure 1 is a schematic of the slotted pipe experimental apparatus. Figure 2 is a photograph of said apparatus, and Figure 3 focuses on the slotted pipe portion of this apparatus. Before starting the experiments, the apparatus has to be cleaned properly to ensure no effects on head loss due to dirtiness in the pipe. The cleaning procedure is as follows:

Pre-Experiment Cleaning Procedure

1. Remove slotted pipe with PVC cap still attached. Remove teflon tape. If algae is growing in the pipe, submerge it in water and add a splash of bleach; if no algae, submerge in acetic acid solution. Leave the pipe in the solution for 15 minutes.
2. Clean pipe out with bristled scrubber if necessary after removing from the cleaning solution.
3. Wrap Teflon tape on non-capped side, leaving 5 slots uncovered, and insert the pipe back into the elbow opening.
4. Rinse out the turbidimeter cuvettes with distilled water and wipe the outside with a KimWipe.
5. Clean the copper pipe leading into the rapid mix chamber by inserting a thin wire in it and scraping out any built-up PACl that may be in the pipe.

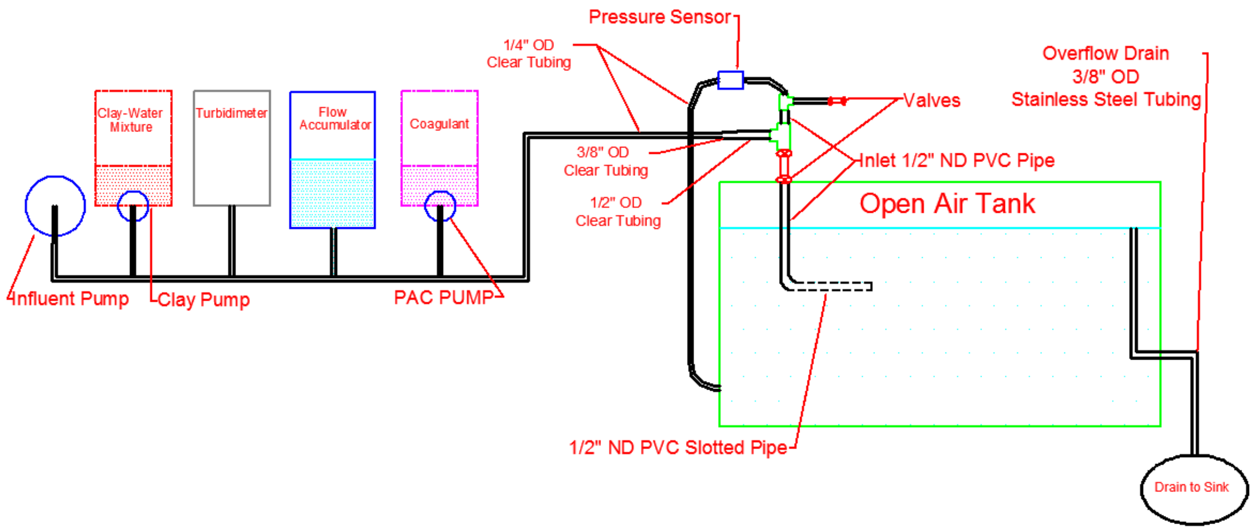


Figure 1: Slotted Pipe Experimental Apparatus Schematic

After the apparatus is cleaned, the Process Controller (PC) state is set to *Pre-Filter* (See *PC States* two pages below). The purpose of each component of the set-up is described in the following list:

a. Before starting an experiment, the open-air tank is filled with water.
b. The water level is at the height of the overflow drain, which is a steel pipe open at the top.
c. The lower valve is shut.
d. The upper valve valve is opened. This process ensures that all air is removed from the system before starting an experiment. An excess of air in this tube could lead to a faulty pressure reading. With the lower valve still shut, water is pumped into the upper tubes until they are full with water and water flows steadily out of the upper valve. The upper valve is then closed and the lower valve reopened, allowing water to flow through the slotted pipe.
e. If clay is being used for a certain experiment, a clay solution is constantly mixed with an electric mixer.
f. A pump is used to add the clay solution to the influent water.
g. The influent turbidity is held constant with Proportional Integral Derivative (PID) Control, where a turbidimeter measured the turbidity of the influent water after the clay has entered the system.
h. When running an experiment, an influent pump continuously sends water into the system with a certain clay and/or polyaluminium chloride (PACl) concentration.
i. A flow accumulator bottle maintains a steady flow through the system by preventing pulsing of water from the peristaltic pump.
j. A PACl solution is located on a balance so that the change in mass can be measured with time. The PACl stock concentration is 4.768 g/L Al.
k. The PACl solution leaves the stock container via a pump.

l. Coagulant is added to the influent water through a small pipe in a rapid mix chamber to simulate flocculation and coagulation.
m. After flowing through the rapid mix chamber, the water then flows through the slotted pipe and out of the slots. The slotted pipe at the bottom of the tank is capped at the end.
n. As seen in both Figure 2 and Figure 3, the water overflows out of the system through the drain pipe (b), and flows through tubing leading to the sink.
o. A pressure sensor measures the difference in pressure (and thus the head loss) between the inlet tubing at the ¼” OD tubing and at the bottom of the tank.

Figure 2: Slotted Pipe Experimental Apparatus

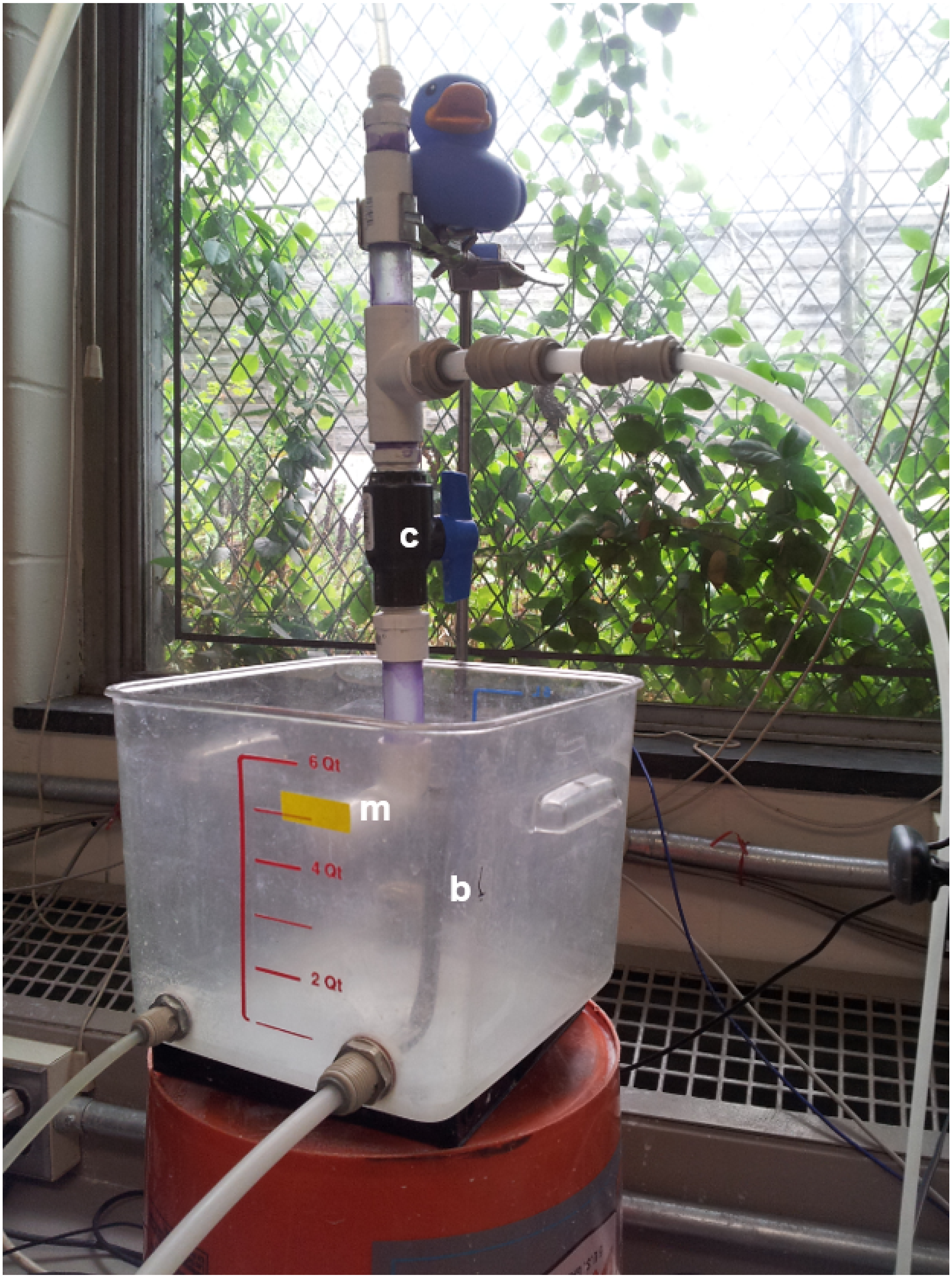


Figure 3: Slotted Pipe Experimental Apparatus

The apparatus models the system of the 0.305 m (12 inch) diameter enclosed stacked rapid sand (EStaRS) filter, as set up by the Enclosed Stacked Rapid Sand Filtration Team (formerly the Low Flow Stacked Rapid Sand Filter team). Instead of multiple filter layers of slotted pipes, one slotted pipe was used. Since water leaves the slots in parallel, the head loss across one slot is a sufficient measure of head loss across every slot.

The flow rate through the entire EStaRS filter is 0.8 L/s. There are four inlet pipe layers. Since the upper and lower pipe layers have slots on only one half of the pipe, these two pipe layers can be approximated as one pipe layer, giving an effective total of three pipe layers. The flow rate through the main inlet pipe in each layer is 0.27 L/s. By approximating each layer as one consolidated length of slotted pipe, the total length of slotted pipe per layer is 74.5 cm (Mehta, Seidner, Sinclair, & Zhu, 2014). Thus, the flow rate per length of slotted pipe is 0.36 L/(m*s). Given the center-to-center spacing between each slot, B_{Slot}, which is 3.175 mm (0.125 in), the flow rate through each slot, Q_{Slot}, is 1.14 mL/s. Since the maximum upper bound of a possible flow rate using one 100 RPM pump is 360 mL/min, the resulting slotted pipe length for this flow rate is 1.77 cm. This pipe length allows for a total of ten slots, with five on each side. The apparatus was then constructed based on having this number of slots available on the slotted pipe.

Rapid Mix Chamber Clogging

After measuring the change in mass of the PACl stock tank for the duration of the experiment, it was noted that PACl was entering the system at slower and slower rates over time. This decreasing rate of PACl addition indicated that the system was clogging. This means that an upper bound of 26.5 mg/L Al could be established for the rate of PACl needed to enter the system in order for the slotted pipes to accumulate high levels of head loss, some up to 30 cm, and therefore clog the slotted pipe. Further observation showed that the pipe into the rapid mix chamber was clogging. Clogging of PACl occurred in the small pipe due to a suction force that caused water to be “sucked” up into pipe, raising the pH of the liquid in the pipe and causing the PACl to precipitate. The suction force was caused by the PACl peristaltic pump, exerting varying pressures on the PACl tube. Therefore, a new peristaltic pump was used, one which has six rollers, instead of the previous one, which had three. The increase in rollers on this pump allows for a more consistent flow of PACl and more consistent pressures on the tube. After the insertion of the new peristaltic pump, clogging in the rapid mix chamber pipe stopped.

Slotted Pipe Experiments

In order to clog the slotted pipes and measure the resulting head loss, a range of coagulant dosages and influent turbidity levels were tested on the slotted pipe. The coagulant-clay ratio is suspected to be a deciding factor in floc buildup on the slots. The mass of clay and coagulant accumulated on the slots would also affect future water flow through the inlet pipe

Table 1 below gives a summary of the different combinations of conditions for all experiments run.

Table 1: Experiment Conditions

PACl Dosage (mg/L Al)	Average Influent Turbidity (NTU)	Clay Added After Time t = 0
0	~500	No
<10.6	< 1	No
	~500	No
<26.5	< 1	No
	~375	Yes
	~500	No
	~500	Yes
26.5	~500	No
	< 500	No
<60.8	< 1	No

Since one main purpose of the slotted pipe experiments is to determine at which point the slotted pipes will clog, water with a high influent turbidity and PACl concentration was used. These conditions allow for a shorter runtime compared to the 12-hour experiment performed last semester with the Stacked Rapid Sand Filter apparatus. Experiments were initially run at 0.5 hours, then increased to 3 hours, then increased to 6 hours as it became apparent that longer runtimes were needed to see trends in head loss.

For the slotted pipe experiments, the influent turbidity was 500 NTU and the coagulant concentration was 10.6 mg/L Al. These values were chosen because the clay to coagulant ratio would be the same as influent water with 5 NTU and 0.1 mg/L Al, which is more similar to sand filter conditions in AguaClara treatment plants. Therefore, if these high turbidity and coagulant levels do not cause clogging or significant head loss across the pipe, it would suggest that the head loss across the slotted pipes will be negligible for most conditions. However, if significant head loss were found across the slotted pipes in these conditions, then additional experiments would be run with lower coagulant concentrations and lower influent turbidities.

After running an experiment with only PACl entering the system at 10.6 mg/L Al and seeing that head loss continued to increase significantly, it was decided to increase the coagulant dosage to 26.5 mg/L Al. Raising the coagulant dosage would test the hypothesis that coagulant was the primary reason for clogging the slotted pipe.

Further observations with experiments with only coagulant show that the head loss leveled off after 2 hours. In order to see how clay would add to that head loss, a different set of experiments were run. The experiment would start with only coagulant being added continuously to the system. Once it was observed that the head loss was leveling off, a clay-water mixture at a high constant turbidity would start entering the system continuously. These experiments would show whether the coagulant or clay added contributed to head loss more.

Slotted Pipe Process Controller Method File

A Process Controller method file was written to control the solenoid valves and pumps for the experiments with the slotted pipe. The following states and setpoints are used:

States

- **Off:** All pumps off, solenoid valve closed.
- **Pre-Filter:** Influent flow pump on, solenoid valve closed. Water fills up the flow accumulator bottle enough so that air is not pumped into the system. Water fills up the tank until the water level reaches the overflow drain level.
- **Filter (PACl):** Influent flow pump, PACl pump on, solenoid valve open.
- **Filter (PACl and Clay):** Influent flow pump, PACl pump, Clay pump on, solenoid valve open.
- **Calibrate:** Set pump speed to 5% or 95% of total pump speed as necessary to calibrate the peristaltic pumps.
- **Toggle:** Set solenoids to the Toggle setpoint to check if solenoids are working properly.

Setpoints

- **Off/On:** Correspond to boolean 0/1, respectively. Can be used to turn pumps off/on or switch solenoid valves from closed/open.
- **Turbidimeter:** Includes an ID number and turbidimeter reading.
- **Pumps:** Includes fractions, flow rates, pump ID number, stock concentration, and desired concentration to dictate the speed at which each pump is run
- **PID Control:** Calculates the fraction that the pump should run based on given values for P, I, D, a target value, and a setpoint value in constant-time. Used for the clay pump to maintain a target turbidity. The given values are as follows: P = 0.273, I= 0.361, D=0
- **Runtime:** Determines the length of time to run a certain state before switching to the next state (used only when in automatic mode)

Clogging and Failure Points

Filter and slotted pipe performance was measured by certain checkpoints in clogging and head loss. Clogging is defined as obstructing an opening or pore so thoroughly that water cannot pass through the opening. Clogging may occur for individual pores or for the slotted pipe as a whole. Complete clogging of the slotted pipe is unlikely since the velocity of the water increases when the exit area becomes smaller, allowing water to shear particles off of the surface and keep slots partially open. Partial clogging of the slots has been observed, where some slots are sealed off with clay and coagulant.

Since complete clogging is improbable and partial clogging is difficult to quantitatively characterize, other failure points are defined to assess the slotted pipes. The head loss accumulated over time measures how much potential energy is lost in heights of water. Since only so much head loss can occur over the stacked rapid sand filter as a whole to keep water flowing through the plant, then the slotted pipe should only contribute to a small part of that head loss. The amount of head loss allotted for entire stacked rapid sand filter is about 50 cm, so the slotted pipe head loss should be less than 10% of that maximum value, or about 5 cm.

Biological Growth

After removing the slotted pipe at the end of each experiment, the subteam often noticed that a black growth had formed during the experiment. This growth is highlighted below in Figure 4. Since the growth could be removed by soaking the slotted pipe in bleach solution, it can be concluded that this growth is biological. This subteam speculated that this growth is either algae or bacteria. The subteam used bleach to kill the black growth after each experiment, since biological growth was not intended to be a variable in these experiments, and the team did not want this growth to cause any additional head loss.

Figure 4: Algae Growth in Slotted Pipe

Observed Clogging

After the conclusion of each experiment, clean water was run through the slotted pipe in an attempt to remove any loose clay or PACl particles before the slotted pipe was soaked in bleach or acetic acid solution. When clean water was run through the slotted pipe, the subteam observed that the water came out unevenly across the slots, as shown in Figure 5, below. This also demonstrates that the slotted pipes clog. It can be seen below that more water is exiting through the left side of the slots than the right. To further explore this concept, the subteam ran clean water through a clean slotted pipe, and the water exited evenly through every slot. This is shown in Figure 6, below. As can be seen below, the water exiting the dirty slotted pipe had a much faster velocity, causing the water to exit upwards, as well. Volumetric flow rate is conserved, and is equal to velocity multiplied by area. Since the velocity of the water exiting increased, this means that the area through which the water exited decreased. This decrease was due to the clogging of the pipes; the clay and PACl had blocked the slots, preventing water from exiting the pipe in those locations.

Figure 5: Clean Water through Clogged Slotted Pipe Immediately after Experiment

Figure 6: Clean Water through Clean Slotted Pipe

Analysis

Slotted Pipe Head Loss

The estimated head loss through the slotted pipe was calculated. The orifice equation was used to approximate the head loss through each slot. Since water exited each slot in parallel, head loss from each of the slots was not additive. The head loss through one slot was the same magnitude of head loss for all of the slots.

Head loss defined by the orifice equation is shown below:

$$h_L = \left(\frac{Q_{Slot}}{\Pi_{VC} A_{Slot}}\right)^2 \frac{1}{2g}$$

Given Q_{Slot} is 1.1 mL/s, Π_{VC} is 0.62, and A_{Slot} is 5.1 mm^2, the head loss through a slot is 0.7 cm. This value seems negligible and agrees with the original hypothesis that head loss through the slots is insignificant.

Experiments from previous semesters tested head loss through copper mesh, which has comparable square openings of 0.23 mm x 0.23 mm. These experiments had varying results showing that after 12 hours of runtime, head loss either linearly increased to values of below 5 cm or above 30 cm. The analysis shows that water flowing through the slotted pipes has minimal effect on overall head loss. However, since clogging has proven to be a major issue with pipes in AguaClara treatment plants, it is expected that clogging will result in higher head loss values.

Slotted Pipe Experiments

The head loss graphs for the experiments run with various conditions were plotted together and shown below.

Clay Only

Two experiments were run with only clay entering the system. Both experiments were run for 6 hours with an influent turbidity of 500 NTU.

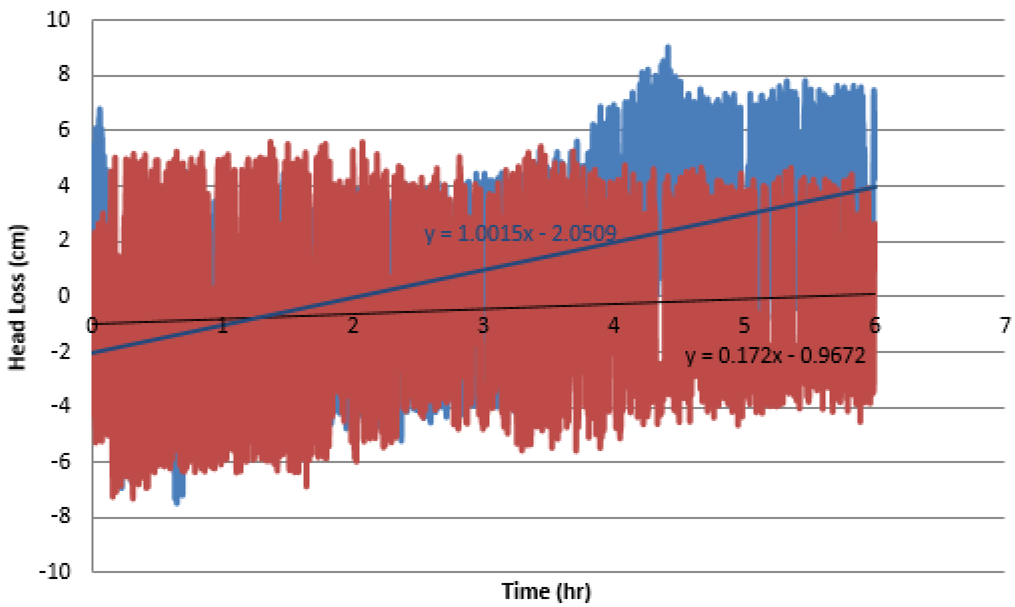


Figure 7: PACl: 0 mg/L Al, Influent Turbidity: 500 NTU

As seen in Figure 7 above, for both experiments, there was only a small increase in head loss over 6 hours. One experiment showed an increase of around 4 cm, and the other less than 1 cm. Though the slopes are relatively different, where one is almost 1 cm an hour and one is about 0.2 cm an hour, these head loss increases over are time are trivial. Clay alone does not seem to contribute significantly to the head loss.

PACl Only

Six experiments were run where only the coagulant, PACl, was sent through the system. One experiment was run with 10.6 mg/L Al; four experiments were run with 26.5 mg/L Al and one at 60.8 mg/L Al in order to clog the slotted pipe more quickly. It was observed that the mixture of clay and PACl was accumulating significantly on the bottom of the tank and might be settling onto the slotted pipe. In response to this concern, the slotted pipe was moved up higher above the bottom of the tank. The position of the slotted pipe is denoted in the legend as ‘higher’ or ‘lower’.

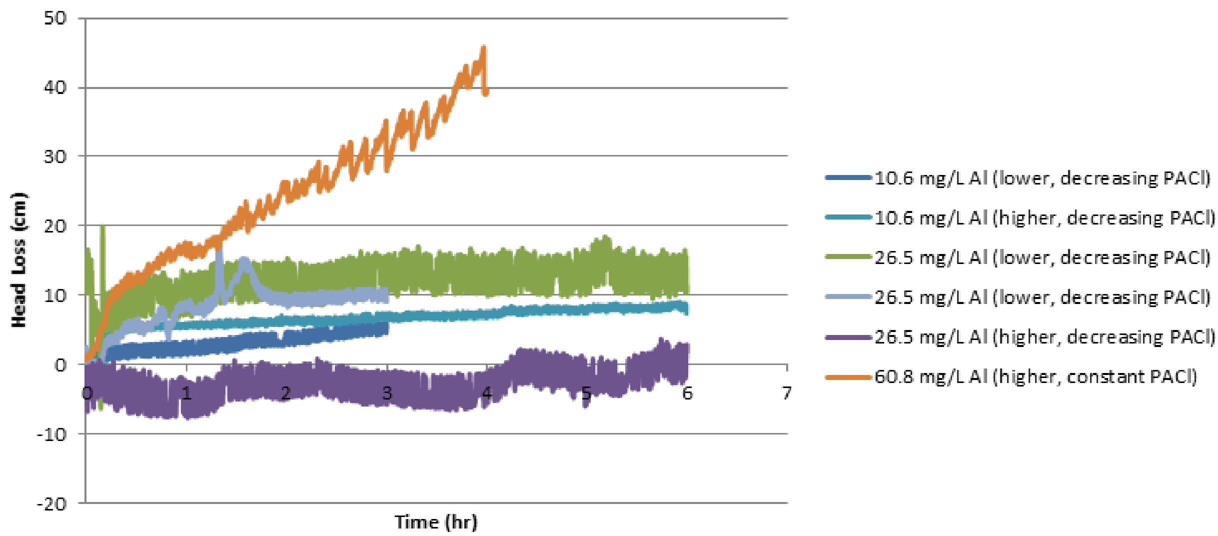


Figure 8: PACl only, Influent Turbidity < 1 NTU; Higher= higher height of slotted pipe in tank; Lower= lower height

The above graph, in Figure 8, shows that there are relatively consistent levels of head loss among experiments with the same conditions. Two of the three experiments with 26.5 mg/L Al achieve similar head loss values and have similar shapes on the graph and the two 10.6 mg/L Al experiments achieve similar head loss values and have similar shapes on the graph. However, one experiment, with 26.5 mg/L Al at the higher height, had head loss values lower than all other experiments. This seems to be an outlier among the data, since the other two experiments at the same conditions had much higher head loss values.

Both higher and lower slotted pipe placements were tested because one potential issue was that head loss readings could be artificially raised since the clay and PACl was accumulating on top of the pipe, which would never occur in an actual filter. The lower position of the slotted pipe (denoted lower in legend) does not necessarily affect the head loss, because the two experiments with a dosage of 10.6 mg/L Al show similar trends, despite one being at the higher position and one being at the lower position.

Five of the six tests were executed with decreasing amounts of PACl flowing into the slotted pipe. As mentioned in the *Methods* section, this decrease in PACl concentration as time went on was due to the rapid mix pipe being clogged with PACl. However, since five experiments were run with the same condition of decreasing PACl dosage, the effect on head loss measured does not vary much from experiment to experiment. The only experiment that experienced a constant PACl dosage was the 60.8 mg/L Al dosage experiment, the one in which the most head loss, around 40 cm, was attained.

For one of the experiments with a PACl dosage of 26.5 mg/L Al, the head loss increases but then begins to level off. In this experiment, head loss increased at an average rate of about 10 cm/hr for the first 1.5 hours, which is a significant amount of head loss for such a short time. After 1.5 hours, the head loss spiked and dropped to about 10 cm, leveling off for the remainder of the experiment. A possible explanation for this drop is that the coagulant may have built up on the openings of the slotted pipe, increasing the head loss. The velocity of the water would have then increased until the velocity was fast enough to remove the coagulant blocking the slots, thus removing areas of head loss. The head loss would then level off at this point because there was a maximum amount of coagulant that would be continually added and removed.

As seen above, an increase in PACl dosage seems to lead to an increase in head loss. The 60.8 mg/L Al dosage leads to the highest head loss, where head loss increases at an average of about 10 cm/hr, with the rate even higher in the first quarter of an hour. The two experiments that yielded the next highest head losses were dosed with 26.5 mg/L Al. The next highest head loss graphs are the experiments with 10.6 mg/L dosages. Aside from the outlying 26.5 mg/L Al graph (shown in purple in Figure 8), these experiments seem to suggest that the head loss generally decreases as the PACl dosage decreases.

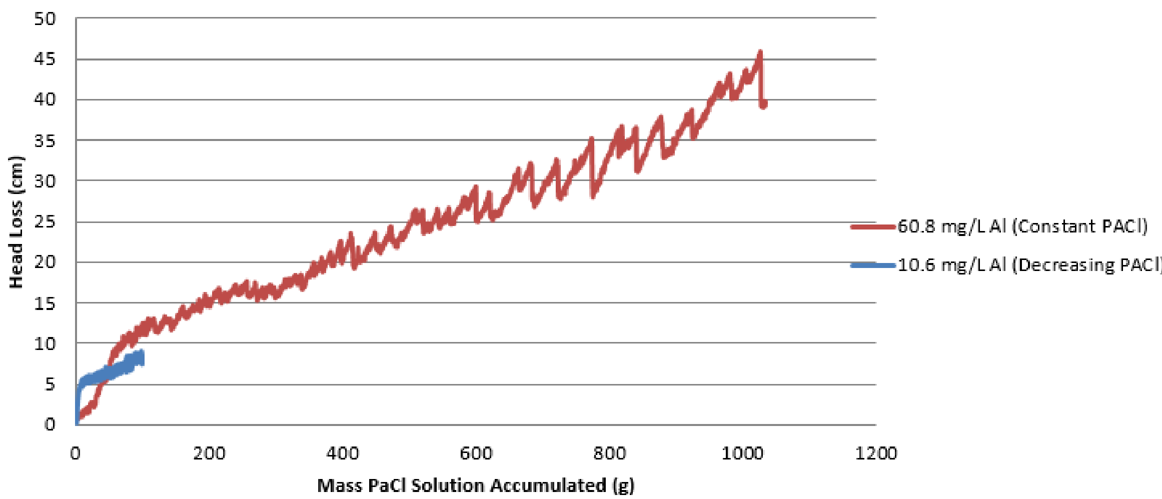


Figure 9: PACl: Varying; Influent Turbidity: <1 NTU; 60.8 mg/L Al run for 4 hours; 10.6 mg/L Al run for 6 hours

The head loss with respect to the mass of PACl solution accumulated is plotted above in Figure 9. The total mass of PACl solution entering the system was calculated. The mass of the PACl stock tank was measured at one-hour intervals for the duration of the experiment. Using the mass measurements for each one hour interval, the amount of PACl solution entering per five-second interval was calculated. The PACl stock tank had a concentration of 4.768 g/L Al. The total amount of solution added was the final mass of the PACl stock tank subtracted from the initial mass of the PACl stock tank.

The above graph shows that much more PACl solution accumulated during the 60.8 mg/L Al run than during the 10.6 mg/L Al run. However, even with the disparity in mass of PACl solution accumulated, the 10.6 mg/L Al graph seems to have a similar shape when compared with the 60.8 mg/L Al graph's shape. The slopes of the two graphs are very similar, especially after the initial growth in head loss. This change from initial growth to a steady increase in slope occurs at approximately 5 grams accumulated for the 10.6 mg/L Al graph and approximately 45 grams for the 60.8 mg/L Al graph.

PACl and Clay

Six experiments were run with an influent turbidity of 500 NTU and a PACl dosage of 26.5 mg/L Al. However, as denoted below in Figures 10 and 11, four experiments had a decreasing input of PACl solution into the system over time, due to the clogging of the rapid mix pipe. Figure 11 shows the same set of experiments at a smaller head loss scale so that trends can be seen more easily.

The experiment in Figures 10 through 14 shown as green had a drop in turbidity during the experiment. The experiment had an influent turbidity of 500 NTU for the duration of the experiment, except between 2.17 hours and 3.08 hours, where the influent turbidity was below 100 NTU. The points where the turbidity was under 5 NTU are the red portions on the graphs for Figures 10 through 14.

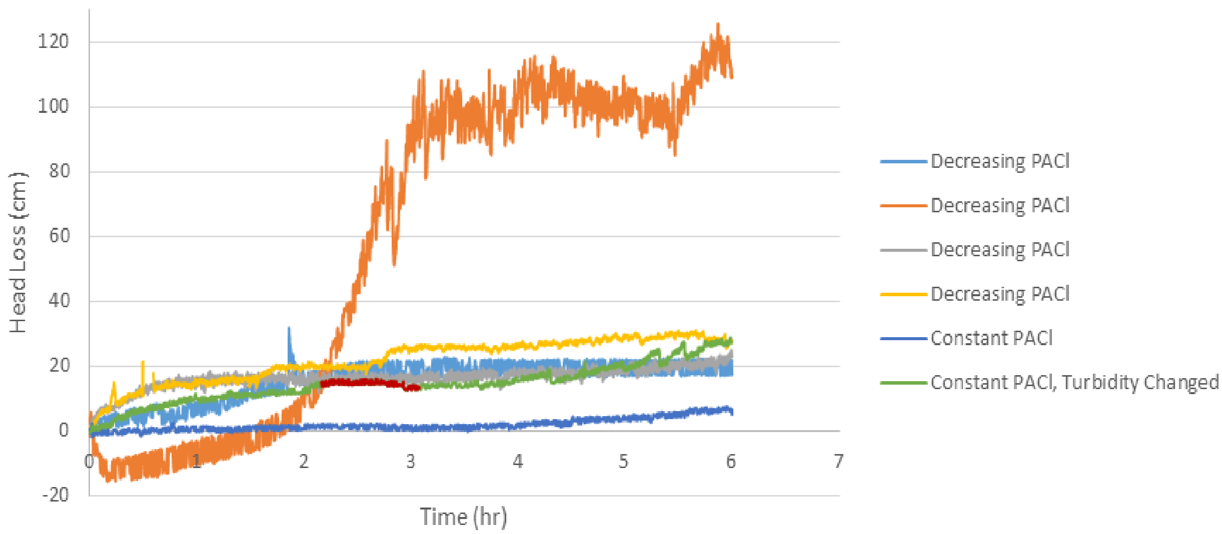


Figure 10: PACl: 26.5 mg/L Al, Influent Turbidity: 500 NTU, Red Line Shows Turbidity < 100 NTU

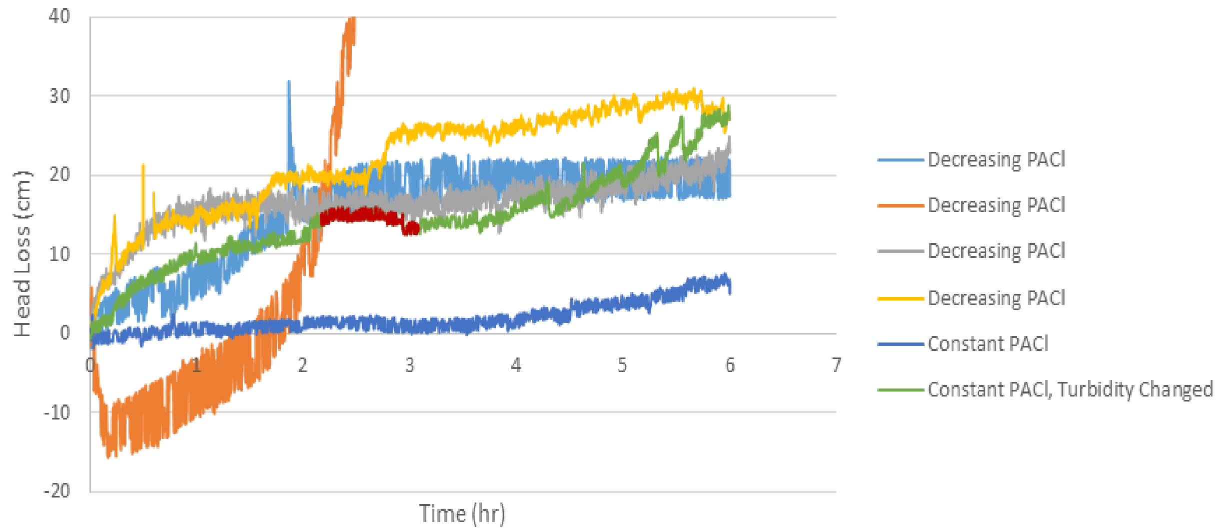


Figure 11: Smaller Scale, PACl: 26.5 mg/L Al, Influent Turbidity: 500 NTU, Red Line Shows Turbidity < 100 NTU

The slowly decreasing PACl addition does not seem to affect clogging as much as expected because four of the six experiments have very similar graphs, where after six hours, the head loss finishes at around 20-25 cm. These four experiments' head losses level off after about three hours, at which point the head losses increase at a much slower rate.

Two of the six experiments are much different than the others, with one experiment reaching 8 cm head loss, and one reaching 120 cm head loss. The experiment with 120 cm of head loss might have achieved such head loss because the slotted pipe may have clogged early. The experiment with only 8 cm of head loss, on the other hand, had constant PACl addition, which would have been a higher level of PACl than any of the other experiments run so far. This level of PACl may not be optimal for creating strong flocs with the clay, thus having less head loss. However, this one experiment with low head loss does not match up with any trends found so far, and needs further replication to confirm these head loss values.

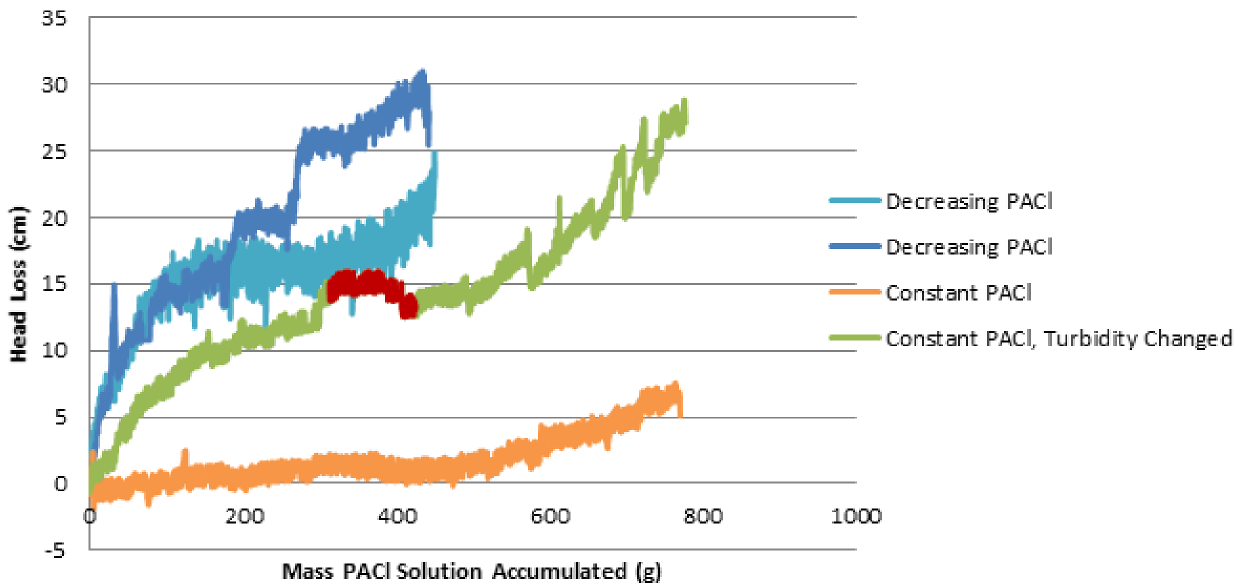


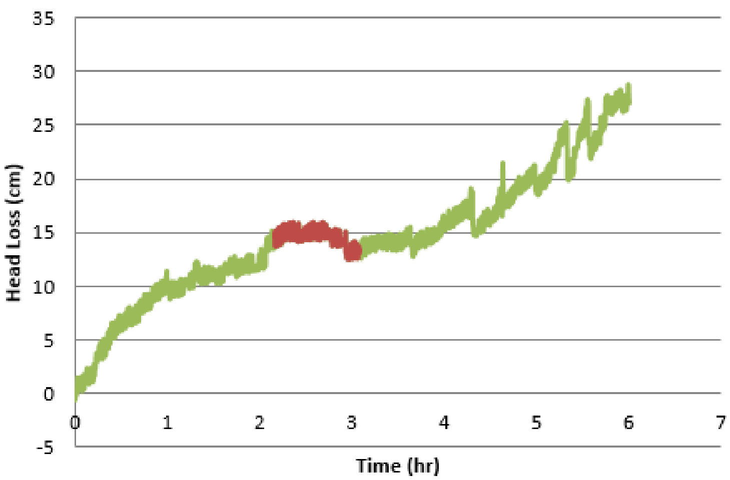
Figure 12: PACl and Clay vs. PACl solution mass accumulated

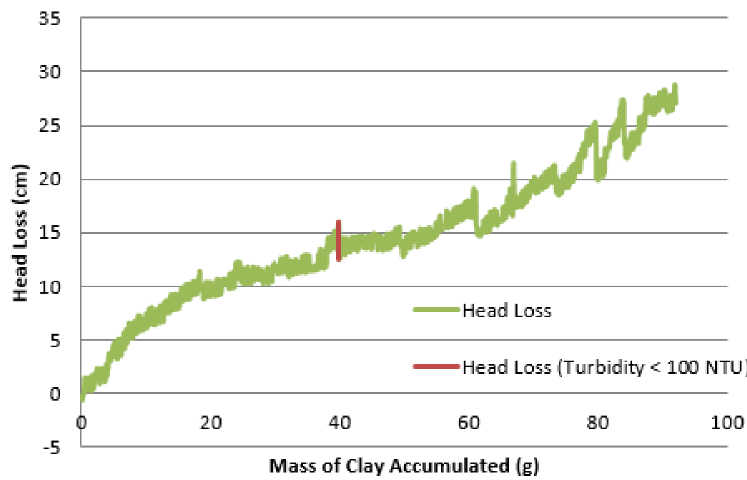
The head loss for the *PACl and Clay* experiments was plotted against the mass of PACl solution accumulated. The same procedure was used to calculate the mass of accumulated PACl solution as was used for the *PACl Only* experiments.

As seen in the above graph, three of the four experiments were run at constant 500 NTU for the entire run. One of the experiments, as explained previously, had a turbidity that fell far below 500 NTU. Even with this discrepancy, the head loss of said experiment shows similarities to two of the other four experiments. In these three experiments, which were virtually the same (except for the fact that the PACl concentration decreased for two of the experiments), head loss gains are pretty similar. Each of these experiment's head losses ended in the 20-30 cm region. The trends of these three graphs are similar in that all begin with sharply rising slopes, then increase steadily in head loss until the end. These trends show some consistency of results for the 26.5 mg/L Al, 500 NTU experiments.

From these experiments it is difficult to tell whether or not the cumulative amount of PACl solution added affects the amount of head loss across the slotted pipes, because even though one of the experiments had the maximum amount of PACl solution added (~800 g), the slotted pipe still did not achieve as substantial head loss as the other three experiments. Likewise, as said before, the two experiments that received roughly 440 g total PACl solution experienced the same or more head loss as the ones that received roughly 800 g total PACl solution, albeit receiving about half the cumulative amount of PACl solution.

The graphs below, shown in Figure 13 and 14, is the experiment where the turbidity dropped from 500 NTU to below five NTU. Both the *Head Loss vs. Time* and *Head Loss* vs*. Cumulative Mass of Clay Added* graphs are shown.





Figures 13 and 14: Clay <500 NTU; PACl 26.5 mg/L Al

As designated by the red regions on the graphs, the period of low turbidity occurred between 2.17 and 3.08 hours into the experiment, and between when the total mass of clay accumulated was 39.7 and 39.9 grams. Head loss was level during this period of time, most likely because there wasn't as much clay entering, which meant that the PACl and clay couldn't form adequate flocs to clog the pipe.

Figure 14 shows that it is possible to essentially neglect this period of time by plotting the head loss against mass of clay accumulated, giving that period a minimal influence on the shape of the graph. Thus, the head loss appears to be more linear when plotted with respect to clay mass added. The two graphs are pretty similar excluding this errant period of time. Head loss increases throughout the experiment and reaches a final value of 27 cm.

PACl and Delayed Clay Addition

Three experiments were run with 26.5 mg/L Al, with a delay in the addition of clay. Each experiment was started with 26.5 mg/L Al and clean water entering the system. When the head loss seemed to reach a steady state value, clay was added to the system to create influent water with a constant turbidity. The head loss plots and the time of clay addition can be seen below in Figure 15.

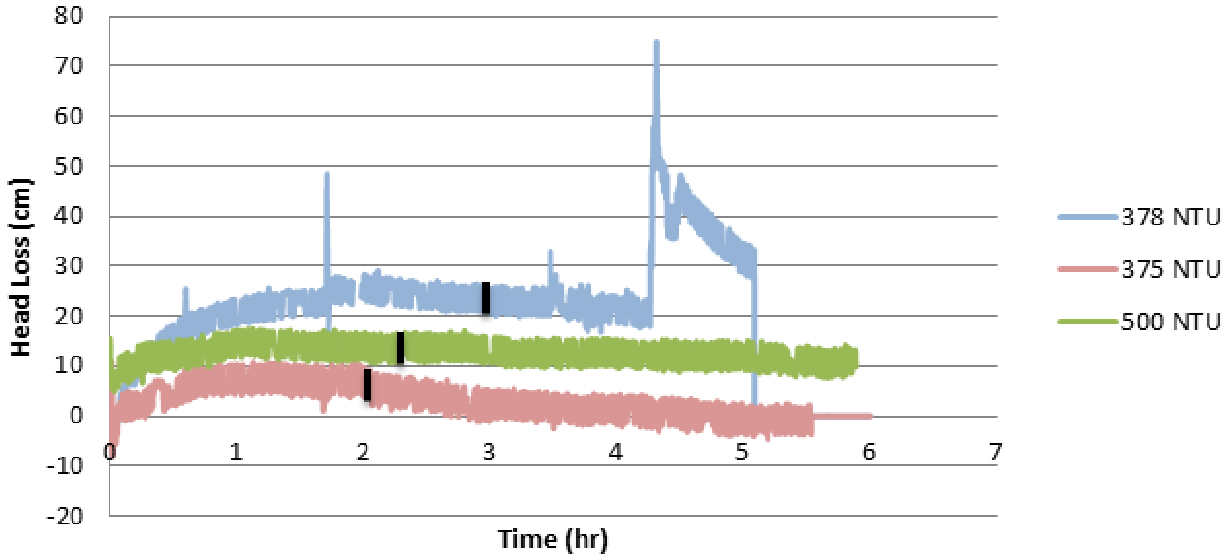


Figure 15: 26.5 mg/L Al; vertical black line indicates when clay was added to the system

For two of these experiments, the head loss started slowly declining after the clay was added. This downward trend did not occur for any other experiments, either the PACl only or the PACl and clay. However, since this slightly downward trend seems to start before the addition of clay for at least two experiments, this trend is most likely independent of the clay addition. For the experiment with an average influent turbidity of 378 NTU, there was a sharp peak in the data about one hour after the addition of the clay. Transitions in head loss are expected to be continuous, so a sudden jump in head loss may suggest experimental error. From this data, it is difficult to determine any trends that occur when both PACl and clay are in the system.

For these three experiments, the head loss over time all follow a similar trend of initial increase in head loss and then a gradual decrease. There is no immediate correlation between clay addition and change in head loss. Regardless of when clay was added, each experiment shows that head loss decreases slowly over time.

Varying PACl and Influent Turbidity Conditions

The following graph, in Figure 16 below, compares the head loss of several experiments with different conditions. There are representative experiments with only PACl added and only clay added. Both experiments with clay and PACl are displayed because the trends are significantly different.

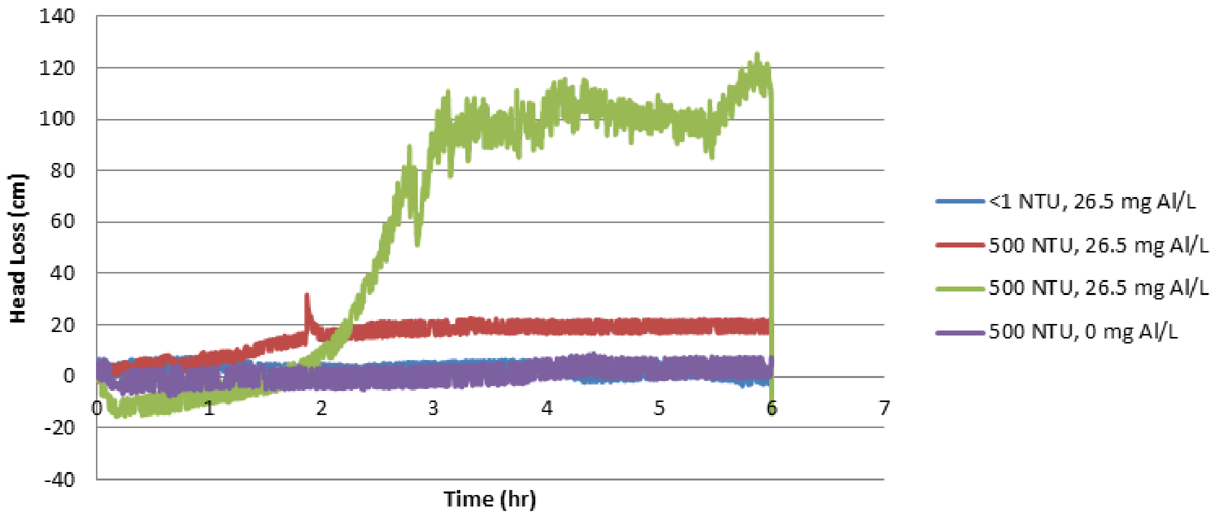


Figure 16: Varying Condition of Influent Turbidity and Coagulant Dosage

From Figure 16 above, simply adding either only coagulant or only clay in the water does not create a significant amount of head loss over time. When PACl and clay are combined, however, head loss increases at a much higher rate. Flocs, or combined particles of clay and PACl, are created and clog the slotted pipe much more easily. Both experiments with PACl and clay have significantly higher head loss than experiments where only one of these were added.

Conclusions

The head loss through the slotted pipes with water alone was calculated to be negligible. The addition of clay and coagulant at varying levels has shown to lead to clogging of the slotted pipe. Experiments with only clay and water running through the slotted pipes demonstrate that there is not a significant amount of head loss from the pipes. The clay and water flow fluidly through the slotted pipe without much build up. Experiments run with only PACl in the system did not reach a steady state head loss, as expected. When head loss is plotted versus mass of PACl accumulated, head loss continues to increase as more PACl is added. This shows that head loss is dependent on coagulant concentration. Perhaps, if these experiments were run for a longer period of time, the head loss would reach a steady state value.

The experimental results showed that slotted pipes clog due to influent water with flocs. Head loss for clay and PACl experiments overall was higher than PACl only experiments, where the influent turbidity is 500 NTU and the PACl dosage is 26.5 mg/L Al. Head loss values for PACl and clay experiments were around 30 cm at the end of a 6 hour run, whereas head loss values for PACl only experiments were around 15 cm. These results suggest that head loss accumulates as a result of flocs clogging the slots. However, plots show that head loss was a function of the mass of PACl that entered the system, whether there was clay present or not. The coagulant may be precipitating out of the water as flocs made of only PACl, thus clogging the slots. Additionally, when turbidity decreased for a period of time, head loss remained constant. This also shows that head loss is dependent on flocs, which are better formed when both clay and PACl are present.

When head loss versus time graphs were plotted, the subteam determined that there is an initial period where head loss increases sharply, for both PACl only and PACl and clay experiments. This period lasts for approximately 0.25 hours, independent of PACl concentration. Additionally, the clogging of slotted pipes was shown when water, entering at the same speed, exited the slots of a dirty pipe faster than a clean pipe, demonstrating that the water was exiting through a smaller area of the dirty pipe.

This semester, this subteam has proved that slotted pipes clog, most likely due to the formation and presence of flocs. Stacked rapid sand filters only have about 50 cm of head loss to work with before too much potential energy is lost. If slotted pipes are contributing so much to head loss, they should be replaced for a better system with less head loss.

Future Work

Given that the slotted pipe leads to head loss values of over 5 cm, and more often near 30 cm, a new injection system should be explored. If the influent water to the filter continues to have flocs that will clog the slots, the slotted pipes will eventually fail due to clogging and accumulated head loss. The StaRS Theory team should collaborate with the StaRS Filter Injection and Extraction subteam to design a new injection system for the StaRS Filter, as well as a replacement for the copper mesh in the small scale apparatus.

However, many of the results describing the performance and head loss of the slotted pipe are largely inconclusive or scattered. Although clogging is definitely observed, the extent to which clogging occurs and how much head loss builds up is still uncertain. In order to better quantify and characterize the flow of water through slotted pipes, more experiments should be run with the slotted pipe apparatus. The experiment with an influent turbidity of 500 NTU and a PACl dosage of 26.5 mg/L Al should be run multiple times, with confirmation that the PACl dosage is constant for the duration of the experiment. Running experiments with these conditions would confirm the apparent trend that head loss achieves around 30 cm of head loss over 6 hours. Since the PACl dosage inconsistency was discovered late in experimentation, more experiments with only PACl and water entering the system would help confirm trends that adding more PACl would lead to more head loss, due to the build up of flocs of PACl that precipitated in the water. Although different PACl dosages were tried, confirmation with a steady PACl injection and known concentration would be helpful.

Stacked Rapid Sand Filter Experiments

After testing the slotted pipe testing unit described above, future experiments would use the sand filter column to learn more about the particle interactions between colloids and sand in flowing water. The team will determine if the sand filter behaves more like a filter, where performance decreases as influent turbidity increases, or a flocculator, in which performance increases as influent turbidity increases. These experiments will be run with the sieved 30-40 sand in the filter column, to avoid segregation in the column during and after backwash. Coagulant dosage will be varied from 0.106 mg/L Al to 1.06 mg/L Al.

The influent turbidity will be kept constant during individual experiments using PID Control. The influent turbidity for all initial experiments will be 5 NTU, which is the maximum turbidity the settled water should be before reaching the filters. The PACl dosages will be varied between 0.106 mg/L to 1.06 mg/L. The following matrices show the resulting clay-coagulant ratio for these concentrations, where 1 NTU is equal to 1.7 mg/L clay.

$$PAC := \begin{pmatrix} 0.2 \\ 0.65 \\ 1.1 \\ 1.55 \\ 2 \end{pmatrix} \cdot \frac{mg}{L} \quad Ratio := \frac{5NTU}{PAC} = \begin{pmatrix} 42.5 \\ 13.077 \\ 7.727 \\ 5.484 \\ 4.25 \end{pmatrix}$$

If different ratios of clay-coagulant are desired, the turbidity can be lowered for the same range of PACl dosages.

Initial experiments will be run at 12 hours because this runtime would be similar to desired runtimes for stacked rapid sand filters. Future experiments may have differing runtimes based on resulting head loss values.

A new injection system to replace the slotted pipes should be designed before using the sand filter column. The current height of sand of 20 cm per layer may also be re-evaluated. Experiments with this modified apparatus will measure head loss and filter performance over time while varying influent turbidity and coagulant dosage, and will eventually lead to a mathematical model of the sand filter.

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