Stacked Rapid Sand Filter Theory

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Abstract

This semester, the goal of the Stacked Rapid Sand Filter Theory team was to create a mathematical model that would analyze the performance of the filter in relation to the amount of clay entering the system at a given time. An experimental Stacked Rapid Sand Filter designed in previous semesters was utilized to model filter performance. A number of experimental tests were run at several PACl concentration dosages to collect data on head loss, influent turbidity, and effluent turbidity. From this data, relationships were graphed and analyzed in order to observe trends in head loss in relation to the mass of entering clay. From this data, an original hypothesis regarding the expected trend in head loss was proven incorrect, and three new theories were proposed in response. Although, progress towards developing a concrete mathematical model are still under way, it is imperative that these new theories are first investigated further in order to understand the inner workings of the Stacked Rapid Sand Filter.

Literature Review

In a traditional surface sand filter, raw water enters from the top of a multilayered filter. As it flows in a direction from top-down, three primary layers act like a sieve to strain out particles and harmful bacteria at the top of the sand bed. The filter consists of a schmutzdecke (a complex biofilm that builds up with the operation of the sand filter), a sand bed, and supporting gravel. Because the flocs, masses of infused clay particles, build up between pores at the top of the filter, a thick layer of particles accumulate at the surface overtime. This accumulation eventually makes up the schmutzdecke and clogs the pores of sand. At this point, failure in the filter is established and a backwash is necessary to continue filter performance. Backwashing is the process of unclogging a filter. In a traditional surface filter, backwashing consists of scraping off the top layers of floc particle build-up [2].

On the other hand, the Stacked Rapid Sand Filter (SRSF) is an AguaClara innovation that is used in conjunction with flocculation and sedimentation. In these sand filters, water is injected directly into the sand bed. Research done in previous semesters has confirmed that Stacked Rapid Sand Filtration is more efficient and also more easily backwashed than a traditional filter [4]. In a SRSF, water flows in through slotted inlet pipes and is able to flow directionally both up and down through six separate sand bed layers within the filter body. Water then flows out through another set of slotted pipes exiting the filter. In order to clean the water through this filtration system, flocs are captured between sand pores as it travels between sand beds. Flocs, as mentioned before, are clay particles coated with coagulant, a sticky chemical that allows these particles to attach to one another. This adhesive property of the coagulant allows the flocs to attach to the sand particles as well. When the water is injected into the sand bed, its velocity increases overtime. This occurs because water starts moving through the sand particle pores which are much narrower in area than the injection pipe. Additionally, as the pores fill with the flocs, the diameter of these sand pores become smaller and the velocity in turn increases as well. This higher velocity increases the magnitude of shear experienced by the flocs making attachment more challenging. At one point, a maximum thickness of floc adhesion will be reached (and thus, a minimum pore size) where flocs will no longer stick to the sides of the tube. Then, the flocs will continue to extend down the tube, leading to filter failure [3]. What is not known, however, is the extent of adhesiveness of these flocs and at what amount of clay added will fill the pores that lead to higher velocities through the system. Through research, the goal is to model the amount of clay in influent water and its relationship to the head loss, pore diameter, and floc adhesiveness of flocs in the movement of water overtime.

Introduction

This semester, the overarching goal of the SRSF Theory sub-team is to develop a mathematical model that analyzes the performance of the Stacked Rapid Sand Filter in relation to the amount of clay and PACl entering the system. Currently, the experimental filter system used allows turbid water to enter through a slotted pipe into the subsurface of the sand filter. As the water flows up or down the sand filter bed to an exiting pipe, flocs are caught between the pores of sand particles and attach themselves to one another or to the sides of these pores. As water flows through the system over time, the flocs continue to build-up along the sides of these pores. This accumulation overtime decreases the diameter of sand pores, which increases the shear force of the water flowing through the filter. It is hypothesized that because of these two factors, the flocs will eventually be unable to attach to the sides of pores, resulting in filter failure. Filter failure is defined as the time when flocs can no longer attach to the sides of sand pores and must therefore exit the filter before being removed from the water. At this point, turbid water entering the system should flow through the entire filter completely unfiltered, making the measurement of effluent turbidity much higher than safe standards. After failure the filter must be backwashed and prepared for another experimental filtration run . This process involves utilizing the computerized process controller to completely backwash the system and remove all accumulated flocs. Being able to predict the time of failure given set variables would allow maintenance to be much more streamlined and eliminate any time or resources spent running the filter past failure and receiving unpotable water. Because of the potential filter failures of the SRSF, the goal of this semester is to experimentally determine the maximum amount of floc build-up that can be tolerated by the filter and the respected diameter of sand pores before head loss and shear are too great.

Additionally, in traditional surface sand filters, water is injected into the filter from the top of the sand bed. Because of this design, and its respective style of accumulation of flocs on the surface of the sand bed, studies have shown that the head loss within traditional filters increases linearly until the filter clogs[3]. At this point in time, the head loss then increases exponentially because of floc build-up on the surface of the filter. Since the Stacked Rapid Sand Filter is designed to inject water differently, allowing flocs to be accumulated within the sand bed, it is hypothesized that the same exponential increase in head loss will not be observed. Instead, it is hypothesized that after filter failure, the trend of head loss will instead begin to level off. This hypothesis is supported by the idea that because the filter will not be clogged on the surface of the filter, similar trends as found in traditional filters will not persist. This can further be explained by a mental visualization of the hypothesized accumulation process within a SRSF. Flocs within the filter column in a Stacked Rapid Sand Filter build-up alongside the perimeters of sand pores. Overtime, this build-up reaches a maximum, where flocs are no longer able to accumulate because of the shear force of incoming water and the limitation of the flocs' adhesiveness. Because of this limiting factor, conditions would remain relatively stable and head loss would be unable to continue increasing, and hence the prediction that it should level off with filter failure. Experimental testing will be used to determine whether or not head loss follows a similar trend as seen in traditional filters after the filter fails.

Methods

Experimental Overview

Research of the Stacked Rapid Sand Filter consisted of running experimental tests with a smaller scaled water filtration system set-up. Instead of the standardized six layered sand beds used in the SRSF, several changes were made to make experimentation more practical. The experimental model used consists of 2 sand filtration layers, each 20 cm deep. These layers are contained within an 1-inch, clear PVC pipe that stands a total of 60 cm tall, sealed at each end. The inlet and outlet pipes attached to this pipe allow the flow rate of water through each layer of the filtration bed to be approximately 1.86 ml/s. This filter column is then attached to a system of devices and pumps to model filtration. This entire experimental apparatus set-up is further explained below.

With this experimental model, several tests at different PACl dosages (0.2

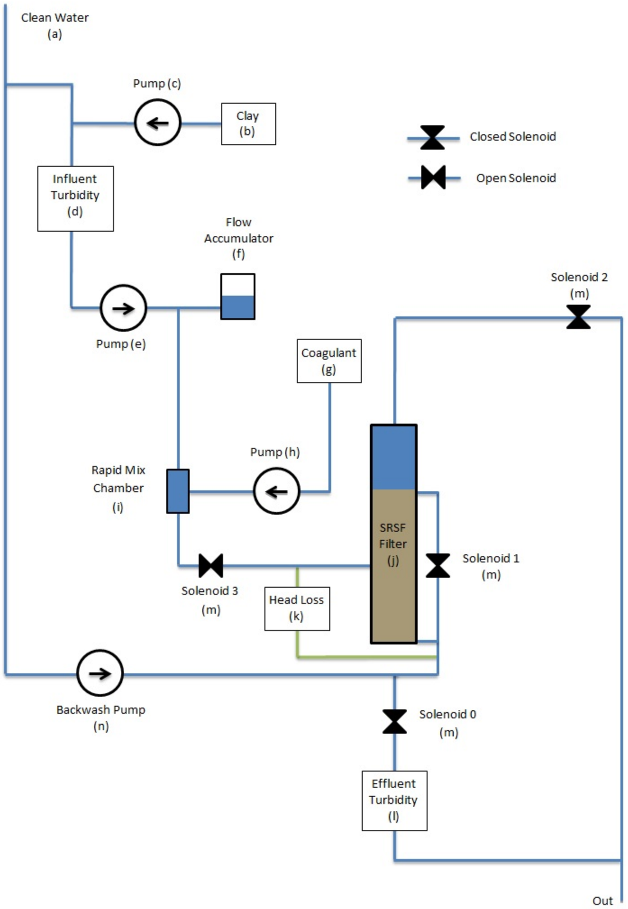

Figure 1: Experimental Schematic

mg/L, 0.65 mg/L, 1.10 mg/L, and 1.55 mg/L) were run and data examining the influent turbidity, effluent turbidity, and head loss were recorded by the Process Controller at every 5 second interval. Following the experimental periods, the collected data was analyzed for any trends that could help create a mathematical model for filter performance.

Description of Experimental Apparatus Set-up

A schematic of the Stacked Rapid Sand Filter model can be viewed below1. The flow through the apparatus is also detailed below.

1. Temperature controlled (20° C) and aerated clean water (a) is stored in a supply tank within the HLS 160 lab.

2. The clean water is then mixed with clay and stored in a stock tank (b). The concentration of the clay and water mixture can be varied based on the desired turbidity. However, clay within the stock tank is currently added by a 1.2 g/L ratio. Later in the semester, however, it was noticed that clogging in the tubing between the stock tank and clay pump was becoming an issue. Because of this, the stock tank was sometimes further diluted in order to prevent clogging in the tubing. This would entail adding extra water, anywhere from half a liter to a liter (depending on the amount of added clay) to ensure the clay mixture was thinned enough. An electric mixer is utilized to homogenize the turbidity of the stock tank.
3. The clay and water mixture from the clay stock tank is pumped into the influent water. Process Controller and PID controls are utilized to control the speed of the clay pump (c). The PID, or Proportional Integral Derivative, control is a feedback system that will properly respond to any discrepancy in the variable and the target value. In this system, the two controls work interdependently to ensure that the influent turbidity into the system remains constant at 5 NTU +/- 0.5.
4. A turbidimeter (d) measures the turbidity of the water entering the filter column before any coagulant has been added.
5. The influent water passes through a peristaltic pump (e) and then through the flow accumulator (f) which absorbs some of the peristaltic nature of the pump and ensures an even stream of water entering the column.
6. Coagulant (PACl) is stored in a stock tank (g) and is pumped into the rapid mix chamber (i) where it mixes with the influent water. Adjusting the speed of the PACl pump (h) can change the PACl dosage added into the system.
7. The influent water, mixed with coagulant, enters the filter column through a slotted pipe into the center of two filter layers. The filter contains two 20 cm sand beds. Some of the water travels upward through the top layer, while some of the water travels through the bottom layer. Sand within the filter traps flocs and reduce the turbidity of the water.
8. A pressure sensor (k) is installed across the sand column. This sensor measures the difference in head between the influent and effluent water. Before every experimental run, the pressure sensor is zeroed when there is no water flowing. During the experiment, changes in head loss are monitored and recorded at every 5 second interval.
9. A turbidimeter (l) measures the turbidity of the water exiting the column.
10. During backwash, a pump (n) fluidized the filter beds between experiments in order to remove the deposited clay and coagulant trapped within the filter column. During the backwash state solenoids 0, 1, and 3 are closed and solenoid 2 remains open. These settings are reversed during the filtration state.

Process Controller Method File

The Process Controller method file used for these experiments contains the following:

States:

- Off: all pumps are off and all solenoids are closed.
- Pre-Filter: The clay pump and filter pump are on; coagulant pump and backwash pump are off. All solenoids are closed. This state is meant as preparation for the filter state by allowing the PID to accumulate data points from which to calculate pump speed to keep a constant NTU and filling the flow accumulator.
- Filter: The clay pump, coagulant pump, and filter pump are on; backwash pump is off. All solenoids except for 2 are open. During this state, the flow of water through (a)-(l) described above is ongoing, and the test is considered in process.
- Backwash (0 and 1): Backwash pump is on; clay pump, coagulant pump and filter pump are off. Solenoid 2 is open; solenoids 0, 1, and 3 are closed. Backwash is meant to clean the filter column between experiments.
- Transition: Filter pump is on; clay pump, coagulant pump, and backwash pump are off. Solenoids 0, 1, and 3 are open while solenoid 3 is closed. Flushes out the remaining particles from the filter.
- 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 set point to check if solenoids are working properly. If the solenoid is working there will be a click.

Set Points: Each of the above states there are a series of set points:

- Off/On: Correspond to Boolean 0/1 respectively. Turns the pumps off/on or switch a solenoid valve from closed/open.
- Turbidimeters: Includes an ID number which allows the information gathered from each turbidimeter to be sorted.
- Pumps: Fractions and flow rates dictate the speed at which each pump is run.
- Runtime: Determines the length of time to run a certain state before switching to the next state. This set point is utilized when Process Controller is in automatic mode.

Experimental Preparation

The procedure detailed below was run through before every experiment in order to cleanse the filter column from the previous experiment and set it up for the new experiment.

1. Change state to Backwash State 0 in Automatic Operation. The following states will be run.
    (a) Backwash State - 5 minutes. In order to allow the sand in the filter column to fluidize more easily, a Backwash 0 state was added. This state should be used. It allows the backwash pump to run at about half the speed before automatically switching to a higher backwash speed of 11 mm/s in the filter column. Tilt the column to fluidize the filter bed and remove any air bubbles as seen necessary
    (b) Transition State - 1 minute. The purpose of the transition state is to push out any remaining flocs from the sand bed.
2. Clean all cuvettes.
    (a) Dump the water in the cuvette and wipe the outside with a Kimwipe. Be sure to wipe away any fingerprints before placing the cuvette back into the turbidimeter.
3. Clean the flow accumulator.
    (a) Dump the water from the flow accumulator bottle. Rinse if necessary.
4. Check that both the clay stock tank and the PACl stock tank are filled at appropriate levels to last the duration of an experiment. The amount of PACl stock needed will depend on the PACl dosage being tested. For PACl dosages between 0.2-0.65 mg/L, experiments can be run with approximately 1.5 L of PACl within the tank or more. Higher PACl dosages such as 1.10 and 1.55 mg/L require the PACl stock to be refilled if the amount is below 2 L. The clay stock tank should be about one-third full before any experiment in order to prevent splattering of the mixture onto the cabinet.
5. Check that all pumps are switched on.
6. Check to make sure the valve from the PACl stock tank and the water supply valve are open.
7. Zero Pressure Sensor in Process Controller.
8. Change state to Pre-Filter on Automatic Operation . The purpose of the transition state is to allow for data points to accumulate so the PID controller can properly adjust the speed of the clay pump to accomplish the desired 5 NTU influent turbidity. Additionally, the flow accumulator will be filled during the pre-filter state. After 3 minutes, the state will switch to Filter for the new experiment.

Experimental Details

Proportional Integrated Derivative

The influent turbidity of the system will be held essentially constant at 5 NTU with an acceptable deviation of ±10%. The PID, or Proportional Integrated Derivative, helps maintain the constant influent turbidity. The code for PID control reads the influent turbidity, evaluates the actual value of influent turbidity relative to the target value of 5 NTU, and then changes the peristaltic pump speed as necessary to achieve the target value. If the turbidimeter reads a value above the target value the PID control sends the value 0 to the pump and the pump stops running. On the other hand, if the turbidimeter reads values below 5 NTU, the PID control sends a value to the pump so that it will start running and reach the desired turbidity [1].

The proportional value, P, is how much in proportion the pump should respond to a high or low turbidity reading. Higher P values correspond to a more responsive the PID is to the changing turbidity. P is also dependent on the concentration of the clay stock. More dilute clay concentrations require the clay pump to be more responsive and therefore the P value should be higher. For these experiments P is set to 1. The integrative value, I, is related to how great the error has been over time. A lower value of I corresponds to fewer previous points from memory are used. These corresponds to a more instantaneous change in the pump. The derivative value, D, is proportional to the rate of change of the error. This value is set to 0.

Analysis

Experiments were run between 18 and 19 hours each at a PACl dosage of 0.2 mg/L during the first week of experimentation. To quantify the filter's performance overtime, pC* curves were created from the experimental data. The data points for these pC* curves were calculated with the following equation:

$pC* = -log(\frac{effluent}{influent})$

This quantity and its respective curves denote how well the filter is performing in cleaning the water. A higher performance curve denotes a more effective filtration and thus, cleaner effluent water. On the other hand, a lower performance curve denotes a less effective filtration. The figure below 2 shows the performance curves of the two experiments run at a PACl dosage of 0.2 mg/L. From this graph it can be seen that after a certain amount of time there is a distinct dip in both curves. The time that each dip occurs is not constant between the two experimental trials. Instead, the first trial's dip occurs after approximately 5.5 hours, while the second test dips after approximately 11 hours. While these two dips both correspond to a decrease in filter performance, its correlation with the pore diameter being too small to effectively trap the clay moving through the system is unknown. The vast change in time between the two dips in each trial is unexpected and difficult to explain. It is hypothesized that this change may be due to a number of potential factors. First, there is a possibility that while backwashing the system, all the flocs from previous trials were not completely removed from the sand bed before the new experimental trial was run. If this is the case, the filter would fail much earlier than a filter starting from a completely clean standard, accounting for the time lapse between the two tests. Another possibility for this difference may be due to human error. Over the course of the first two weeks, PACl dosages and other systematic factors were being varied to make experimental tests more efficient. It is possible that during some of these alterations, something was not properly accounted for or measured correctly. While the influent turbidity stayed fairly consistent throughout the course of experimentation, at around 5 NTU, it is possible that incorrect dilutions of PACl or other miscalculated measurements may have skewed data. While these are only possible explanations, more trials at a 0.2 mg/L PACl dosage should be run to reaffirm and correct mistakes or help articulate these changes between trials.

Following the dipping trend in each experimental trial, however, the filter performance curve is often followed by a slight rise. It was hypothesized that this rise may be due to the flushing out of the flocs after maximum accumulation within the sand bed. In other words, flocs build-up within the filter overtime because of the addition of PACl and resulting accumulation. This in turn clogs the sand pores within the filter. This series of events would then be responsible for the initial dip in the performance curve. However, it is possible that with time the filter pushes out a portion of the floc build-up because of an increase in shear force as the diameter of available pores decreases from the accumulation of flocs. In this case, room would be available for incoming flocs to attach to and once again build up on. This would cause the performance curve to begin to increase again. As seen from the graphed pC* curves, this dip and rise trend occurred at several different times for each of the experiments.

Another observation noticed was that at several time periods, pC* sometimes reached negative values. Mathematically, the pC* data value would only become negative when the value of effluent turbidity is greater than the influent turbidity. In a proper, ideal filter, these conditions should never occur. However, it is possible that these isolated incidences may be due to malfunctions in the PID control where the system over corrects and causes the influent turbidity to be too high. It is hypothesized that these values may be due to the time lag in corrections by the PID controller in conjunction to a failing filter. The reasoning behind this hypothesis is as follows. The PID controller varies over time in order to keep influent turbidity as close to 5 NTU as possible. When this value falls short, the PID works to pump more clay into the system. On the other hand, when the influent turbidity is too high, the PID controller reduces the amount of clay entering the system. When this change occurs, there is often a time lag between the pumping in of clay and the resulting change in influent turbidity. This could potentially account for a lower than usual value in influent turbidity. In addition, when a filter begins to fail, effluent turbidity begins to increase because flocs are no longer accumulating within the sand filter. Factoring in these two changes in turbidity, a low influent turbidity and a high effluent turbidity, a negative number calculated for the pC* value, may

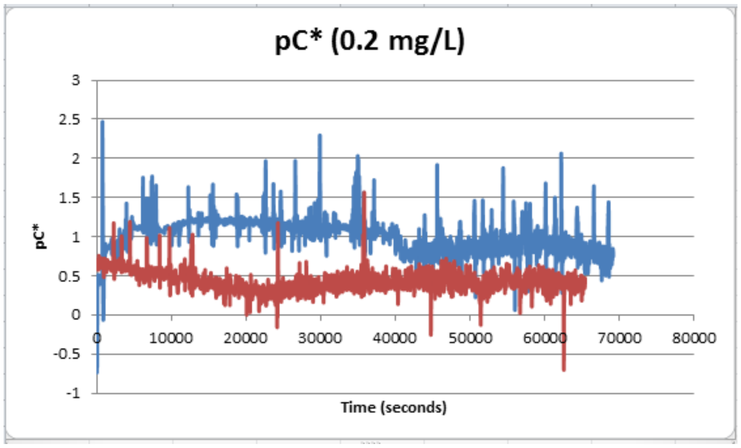

Figure 2: Performance Curve of 0.2 mg/L

be better explained. In addition to this hypothesize, other factors such as leaks and air bubbles within the sand column are currently being observed to see the extent of their role in the skewing pC* values

A total of three experiments with a PACl dosage of 0.65 mg/L were run, and the resulting pC* curves can be viewed below 3. As with the performance curves of the experiments run at 0.2 mg/L, there is a distinct dip in the filter's performance after a certain amount of time. However, the slight increase following this dip is not as noticeable in this set of data. In these experiments, the time that each dip occurred varied with each experiment as well. The first trial's pC* began to dip right after the first hour, while the second and third trial's pC* dipped around 4 hours and 7 hours respectively. The reasons for this trend are still not completely confirmed, but the previous hypothesis still remains unchanged at this point of experimentation.

In addition, the previous observations of negative pC* values is once again noticed. As stated before, the initial hypothesis remains the same. In summary, it is believed that the PID over corrects influent turbidity readings and instantly reacts to counter the change. However, because of the time delay between the influent and effluent readings, the higher effluent turbidity corresponding to this high influent turbidity may happen at a later time when the influent turbidity has fallen back to its lower value thus resulting in the effluent turbidity being higher than the influent.

This hypothesis was later reviewed by looking over the data from past experimental tests for PACl dosages of 0.65 mg/L. It was observed, as previously stated, that at some intervals, influent turbidity spiked to upward values of 7 NTU or higher. Then, upon reviewing data for effluent turbidity, it was noticed that at some instances after these influent turbidity spikes, effluent turbidity would also spike significantly over the current influent turbidity value. This observation confirmed the validity of the original hypothesis over over correction

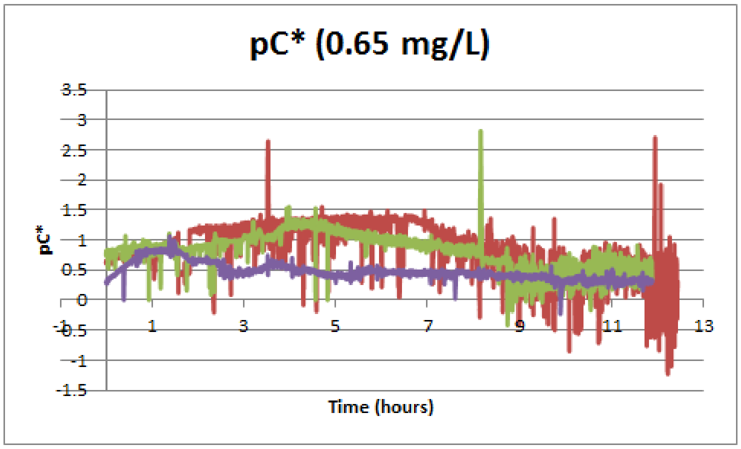

Figure 3: Performance Curve of 0.65 mg/L

of the PID pump. It is possible, however, that other factors are also responsible for negative pC* values.

Following the analysis of each experimental trial's performance curves, the recorded head loss data points were plotted with respects to time. This graph can be seen below 4.

As expected, each head loss curve increases somewhat linearly over time for all of the trials within a given PACl dosage. However, one notable observation that conflicts with a prior hypothesis involves the trend in head loss after filter failure. Initially, it was hypothesized that after failure, head loss values would level off. This hypothesized trend was deduced from previous observations of traditional filters and its respected trends in head loss, an exponential increase. Because the traditional filter and the SRSF inject water differently, an expected difference in trends after failure was also expected. In addition, it was thought that at filter failure, flocs would no longer accumulate along the sides of pores. Because the pore would no longer be decreasing, it was hypothesized, that shear velocity and therefore head loss would also remain constant. In the graphs, however, this leveling off trend does not occur, even after running the filters for approximately 17 hours and ensuring complete filter failure.

Another notable observation made regarded the changes in head loss between PACl dosages. It was observed that in trials with a higher coagulant dosage, a steeper, increasing slope of head loss change persisted with time. On the other hand, in trials with lower PACl dosages, the results showed the opposite, a lower slope change of head loss over time. This general trend in slopes in relation to the concentration of added PACl can be explained by considering the purpose of coagulant in water treatment. The main function of PACl in filtration is to foster particle adherence and accumulation to one another. By adding more coagulant to a given concentration of water, it can be assumed that more particles will come together and produce flocs. This increase in adhesive

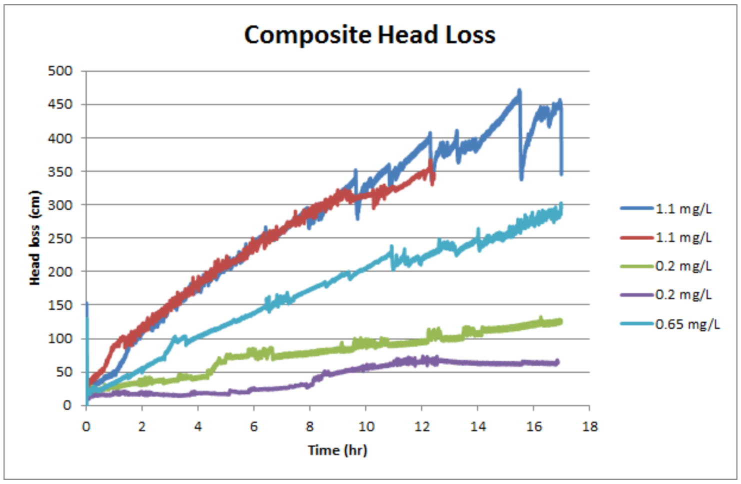

Figure 4: Head Loss of Filter at Several PACl Dosages

ability can also be translated into the ability of flocs to accumulate and stick to void sand pores. With an increased adhesive property, more accumulation will occur in sand pores. This process narrows the diameter of sand pores more quickly, and thus increasing head loss more rapidly. The reverse cause-and-effect process can be applied for adding lower concentrations of PACl.

Mathematical Model Calculations

In order to approach the formulation of a mathematical model relating filter performance and the total mass of added clay into the system, several calculations are required. These calculations include determining an approximation of the minimum pore diameter. This value can be calculated with the collected maximum head loss values. From this, a calculation of the total mass accumulated within the sand bed should also be calculated in order to relate the mass to the change in porosity over time.

Pore Diameter Calculations

To approximate the minimum pore diameter at each of the PACl dosages, the Hagen-Poiseuille Equation was applied. The equation is given by:

$h_f = \frac{32\mu L V_{pore}}{\rho g (d_{pore})^2}$.

The variables in the equation and their significance are as follows:

- h_f is the head loss within the filter. This head loss value is determined by using the data recorded by the pressure sensor during experimental trials.
- V_{pore} is the velocity of water through the pores. It is calculated by the equation $V_{pore} = \frac{V}{\varepsilon}$,where V is the superficial velocity of the water into a void filter column, and ε is the porosity of the sand, initially 0.4.

- L is the length of the sand bed. This value is equal to the length of the sand bed that the water flows through. In this SRSF experimental model, two 20 cm sand beds are modeled, giving a total sand bed length of 0.4 m.
- g is the universal gravitational constant, 9.8 $\frac{m}{s^2}$
- $\mu$and $\rho$are the dynamic viscosity and density of water respectively. These values are tabulated and can be looked up. The dynamic viscosity of water at room temperature is approximately 0.9 x 10^{-3}kg/ms, and the density of water is 1000 $\frac{kg}{m^3}$.

Using this equation and the tabulated values assumes a number of approximations. For instance, the calculations in this research are used to solve for pore diameters within the filter column. However, in order to do so, it must be assumed that these pores extend throughout the entire length of the filter column. In addition, it is assumed that clay and PACl accumulation throughout the column is occurring at a constant rate, producing a constant diameter and velocity throughout the entire length of the column. In reality, however, this is not true; instead, accumulation would more ideally taper off with distance from the position of initial water injection. The velocity of the water throughout the pores is also assumed to be constant throughout the entire duration of the experiment. However, this velocity would really increase with time because of the decreasing diameter width with the accumulation of mass alongside the pores.

Without many of these assumptions and simplifications, these calculations would be too convoluted and would result in too many variables and unknowns. For this reason, such approximations can be temporarily made using the experimental head loss data. From this, the Hagen-Poiseuille equation is utilized to calculate the diameter of the minimum pore for each trial. A sample calculation for an experiment trial using a PACl dosage of 1.10 mg/L can be viewed below:

$V_{pore} = \frac{V}{\varepsilon}$, where V is the superficial velocity, 1.833 m/s, and ε is the porosity of the sand, 0.4. These values are given with the current experimental set-up.

$V_{pore} = \frac{1.833}{0.4} = 4.6$mm/s

Applying the Hagen-Poiseuille equation for a maximum head loss value of 348 cm results in the following calculations:

348 cm $= \frac{32(0.9x10^{-3}kg/ms)(0.20m)(.004583m/s)}{(1000kg/m^3)(9.8ms^{-2})(d_{pore})^2}$

$d_{pore} = \sqrt{\frac{32(0.9x10^{-3}kg/ms)(0.20m)(0.004583m/s)}{(1000kg/m^3)(9.8ms^{-2})(3.48m)}}$

$d_{pore} = 27.8\mu m$

This same calculation was applied to all of the experimental data, and a table containing the maximum head loss, minimum diameter of a pore, and percent difference at each PACl dosage can be viewed below1. As can be seen in the table, the diameter of the minimum pore decreases as the PACl dosage increases. These results make sense theoretically, because the additional PACl dosage increases the stickiness of the flocs. This increase in adhesiveness should allow for more floc accumulation alongside the sand pore before the shear force is too large and accumulation is no longer possible.

PACl dosage	Maximum Head loss	d_{pore}	Percent Difference
0.2 mg/L	121 cm, 64 cm	$47.2\mu m$, $64.8\mu m$	31.5 %
0.65 mg/L	285 cm	30.7 μm	N/A
1.10 mg/L	442 cm, 348 cm	$27.8\mu m$, $24.7\mu m$	12.0 %

Table 1: Results for Pore Diameter Calculations

By using this method, the final values for the resulting diameters of the sand pores seemed to make sense. Larger concentrations of PACl dosages resulted in smaller diameters because of the increased strength in bonds between floc particles. However, with further inspection of the head loss, the proposed method seemed to be invalid. Referring to**??**, the values of head loss seem to continue to increase linearly over time. What was originally hypothesized - that head loss would level off at a maximum - did not hold true. Despite the fact that effluent turbidity and pC* values indicated the filter was no longer cleaning effectively, the increasing head loss demonstrated that flocs were still becoming attached to pores. This made choosing the head loss value to be used in calculating the pore size difficult and susceptible to error. Because of this inconsistency, it was noted that the current head loss used, the proposed "maximum" was in fact just the maximum at the time, and not the maximum of the overall PACl dosage. In other words, the maximum head loss value was a function of time, and it would be constantly changing, depending on the run time of experimental trials. Therefore, data calculated and what was originally concluded as the minimum pore diameter did not hold true.

Although the previous hypothesis was not observed, the head loss does exhibit some trends that lead to new theories for testing. As can be seen in the composite graph of the head losses for experiments with different PACl dosages, the head loss increased more rapidly at higher PACl dosages **??**. Given that the influent turbidity at any given time remains relatively steady at 5.0 NTU, the amount of clay within the system should be the same at any given PACl dosage at the same experimental time. Since the mass of clay entering the system is relatively constant and the head loss trends are still dramatically different, it was suggested that the amount of clay was not a strong determinant of head loss. The graphs of each head loss curve were then normalized for the amount of PACl within the filter at any given experimental time. The calculations for normalizing the data are as follows:

$Mass_{Coagulant} = (Pump_{fraction})(Q_{max})ct$

The variables in the equation and their significance are as follows:$P_{fraction}$is the speed at which the pump is running at. This value can be determined by looking at the settings within Process Controller.

- Q is the flow rate. This value is equal to 6.0 ml/min because of the tubing size used, size 13.
- c is the concentration of the PACl being added.

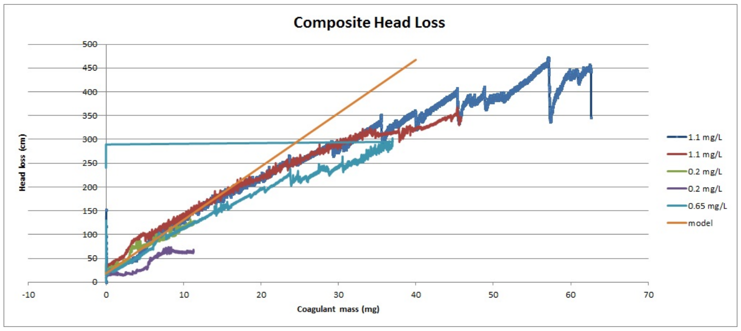

Figure 5: Head Loss Normalized for Mass of PACl in System

- t is the time in seconds between each recording interval, 5 seconds.

By using this equation and calculating a normalized data set, the following graph was created5. It can be seen that the normalized head loss graphs all follow a similar trend. For any given amount of PACl in the system, there should be a relatively similar corresponding head loss.

This lack of a leveling-off in the head loss trend is not what was originally predicted and instead requires a, if not a number of, new ideas and theories to explain its occurrence. Currently, from experimental data for PACl dosages of 0.65 mg/L and 1.1 mg/L, head loss values increase way beyond the expected levels of head loss for the dimensions of the experimental filter column without the proper responses. For instance, the experimental trial depicted by the dark blue trend (PACl dosage of 1.1 mg/L), shows head loss at values around and even greater than 450 cm. In a filter column with only 40 cm of sand bed, it would be expected that with such great head loss values, an uplifting of the sand would be observed. However, during experimentation, this was not seen. Because of this, new explanations had to be formulated. Below are three theories that are being proposed to summarize the continuously increasing trend in head loss:

1. By increasing the concentration of PACl, a resulting increase in bonds between floc particles is also expected. These stronger bonds would then translate into stronger, more tightly held accumulations between particles. It is possible that with these stronger bonds, the flocs are also more tightly held against the sides of the filter column. If this were the case, the build-up of flocs and the strength in bond would prevent the sand particles and the overall sand bed from being lifted, producing a much greater increase in head loss than originally thought possible.
2. There is a possibility that flocs exhibit “fractal behavior.” In other words, flocs may consist of a different ratio of components dependent on the PACl dosage used. When increasing the PACl dosage, larger floc sizes may contain more water than its counterparts. If this theory holds true,

PACl dosage	Maximum Head loss	d_{pore}	Percent Difference
0.2 mg/L	N/A	N/A	N/A
0.65 mg/L	144.4 cm	$43.18\mu m$	N/A
1.10 mg/L	218 cm, 204 cm	$35.15\mu m$, $36.25\mu m$	12.0 %

Figure 6: Minimum Pore Diameters

increased concentration of PACl would produce flocs of lower densities. Lower density flocs would then allow more accumulation because of its high contents of water, and therefore produce higher head loss.

3. Lastly, it has been proven that mass accumulation and the resulting head loss is more dependent on the concentration of PACl, rather than amount of added clay. By increasing the PACl dosage in an experimental trial, more coagulant is also being added into the filter column and thus more mass. Overall, an increase of mass accumulated within the pore would result in a smaller pore size and an overall greater head loss.

With these theories, the new task at hand became proving one or more of these hypotheses. In order to prove or even disprove one or more of these theories, the density of flocs within the pore at different PACl dosages was calculated. This was done by taking the head loss at a redefined filter failure time. This time was defined by when effluent turbidity became 50% of influent turbidity, or at approximately 2.5 NTU. From this, the pore size was calculated with the Hagen-Poiseuille equation as before. From this pore size and the amount of PACl and clay known to be in the system, the density within the pore was calculated. The results for the pore size can be viewed in the table below6 along with a sample calculation using the data from the 0.65 mg/L trial. It should be noted, however, that data for experimental tests run at 0.2 mg/L were not calculated because its effluent turbidity never reached values around 2.5 NTU even over the course of a 17-hour experimental period.

Using the data sheet recorded over the entire duration of the experiments, head loss data was retrieved for when the effluent turbidity began to average 2.5 NTU. The head loss at this value was approximately 144.4 cm. The other values remained the same as previous calculations.

$h_f = \frac{32\mu L V_{pore}}{\rho g (d_{pore})^2}$.

144.4 cm $= \frac{32(0.9x10^{-3}kg/ms)(0.20m)(.004583m/s)}{(1000kg/m^3)(9.8ms^{-2})(d_{pore})^2}$

$d_{pore} = \sqrt{\frac{32(0.9x10^{-3}kg/ms)(0.20m)(0.004583m/s)}{(1000kg/m^3)(9.8ms^{-2})(1.444m)}}$

$d_{pore} = 43.18\mu m$

As seen in the previous method of calculations, the current calculations hold trends as observed as before. Larger concentrations of PACl result in smaller final pore diameters.

Mass Accumulation Calculations:

The amount of clay entering the system at any given time was calculated using the following equation:

$M_{Clay\ Added}(mg) = 1.7QCt,$

where the constants and variables are as defined:

- 1.7 is a proportionality constant relating the turbidity of the water to the amount of clay in the water.
- Q is the flow rate, which is equivalent to1.858 ml/s.
- C is the turbidity of the water in NTU. This value should be relatively constant at 5.0 NTU, and
- t is the time interval between each recording of data, 5 seconds.

This equation was utilized in order to calculate the mass of clay entering and the mass of clay leaving the system. To do so, the measurements from the influent and effluent turbidimeters of each experimental trial were used. The amount of clay remaining in the filter was determined by subtracting the amount of clay leaving from the amount of clay entering. A running value was kept throughout the experiment to determine the amount of clay within the filter at the end of the experiment. A sample calculation for the mass of clay accumulated for a PACl dosage of 1.10 mg/L can be seen below:

$M_{ClayAdded} = (1.7mg/L)(0.001858L/s)(5.1575NTU)(5s) = 0.08145mg$

$M_{ClayRemoved}$: $(1.7mg/L)(0.001858L/s)(5.00NTU)(5s) = 0.0078965mg$

$M_{Accumulated}$: $0.08145mg - 0.0078965mg = 0.0735535mg$

By summing up the mass of clay accumulated during each 5 second interval, the total mass accumulated within the filter column can be calculated for. At an effluent turbidity of 2.5 NTU, the mass of clay accumulated for the 1.10 mg/L PACl dosages was 220.54 mg and 249.1463 mg. For the 0.65 mg/L dosage, 1126.44 mg/L.

PACl Accumulation Calculations

The PACl accumulation was calculated from the known constant speed of the pump. The PACl pump in our apparatus utilizes size 13 tubing. From the AguaClara wiki, it was noted that the maximum flow rate of a pump with this tubing size is 6.0 ml/min. At a PACl dosage of 0.65 mg/L, the pump is running at 12.077% of its full speed. The pump runs at 20.438% of its full speed at 1.10 mg/L PACl dosage. Dimensional analysis was used to determine the amount of PACl accumulated in the filter at the time the 2.5 NTU reading was reached. Since the purpose of the PACl is to make the flocs sticky in order to adhere to the pore walls, it was assumed that the majority of the PACl entering the system remained in the system until backwash. Sample calculations can be viewed below.

PACl dosage	Mass Accumulated (mg)	Volume Accumulated (m^3)	Density of Flocs (mg/m^3)
0.65 mg/L	1126.7351 mg	8.552374 x 10^{-13}	1.317
1.10 mg/L	220.9117 mg, 249.1463 mg	2.1341337 x 10^{-11}, 2.345 x10^{-11}	1.035, 1.062

Figure 7: Density of flocs

$M_{PACl} = (Pump_{fraction})(Q_{max})(Dose_{PACl})(t_{experimental})$

1.10 mg/L: $(.20438)(\frac{6.0mL}{min})(\frac{L}{1000mL})(\frac{1.0mg}{L})(\frac{60min}{hr})(4.616hr) = 0.3736mg$ where 4.616 hr is the experimental time at which the filter failed

0.65 mg/L: $(.12077)(\frac{6.0mL}{min})(\frac{L}{1000mL})(\frac{1.0mg}{L})(\frac{60min}{hr})(10.547hr) = 0.2981mg$

Therefore the mass of the flocs can be determined simply by adding the mass of the clay accumulated to the mass of the PACl accumulated.The results for the mass of the accumulated flocs can be viewed in the table below.

Calculating the Volume of the Flocs Accumulated

The volume of the flocs accumulated was calculated by taking the difference of the initial pore size and the final pore size as determined by the Hagen-Poiseuille equation. The mass of the accumulated flocs was then divided by the volume of the accumulated flocs in order to determine the density of the flocs at the different PACl dosages. The results for these calculations can be viewed in the table below7. As can be seen, it was determined that the flocs at the higher dosage of 1.10 mg/L were less dense than the flocs at 0.65 mg/L.

Conclusions

After running several experiments for 12 to 19 hours each at various PACl dosages and analyzing the respected data and performance curves, it was determined that there was a decrease in filter performance after a certain amount of time. Performance curves for each of the trials were graphed and analyzed for any potential trends. Each of the performance curves showed a sharp decrease in performance which may be connected with the flocs' inability to attach to the pore walls leading to the filter's inability to clean the influent water. After the dip in the performance curve a slight increase in filter performance was noted, most notably in trials running with PACL dosages of 0.2 mg/L. This increase could be correlated to an additional capability of the pores to capture flocs after some flocs were knocked out by a high shear force. However, the dips in the performance curve occur at very different times which makes pinpointing the time of failure and the maximum possible amount of clay within the pores difficult.

The initial goal for the semester was to determine the maximum amount of clay that can accumulate within a pore before the shear force became too high for the flocs to attach. The plan was to utilize data extracted from a head loss graph modeling a leveling off of head loss after filter failure. This data would serve as the maximum head loss value and would be plugged into the

Hagen-Poiseuille equation to determine the minimum pore size. However, the head loss did not level off as was expected and determining the maximum head loss was not possible in such a simple manner.

Because of this contrast between theoretical and actual experimental results, the original hypothesis needed to be slightly altered to explain for the trend in head loss after filter failure. As stated before, three theories were proposed to account for the increase in head loss after filter failure. They are listed as follows:

1. By increasing the concentration of PACl, a resulting increase in bonds between floc particles is also expected. These stronger bonds would then translate into strong, more tightly held accumulations between particles. It is possible that with these stronger bonds, the flocs are also more tightly held against the sides of the filter column. If this were the case, the build-up of flocs and the strength in bond would prevent the sand from being lifted, producing a much greater increase in head loss.

2. There is a possibility that flocs exhibit "fractal behavior." In other words, flocs may consist of a different ratio of components dependent on the PACl dosage used. When increasing the PACl dosage, larger floc sizes may contain more water than its counterparts. If this theory holds true, increased concentration of PACl would produce flocs of lower densities. Lower density flocs would then allow more accumulation because of its high contents of water at lower densities, and therefore produce higher head loss.

3. Lastly, it has been proven that mass accumulation and the resulting head loss is more dependent on PACl dosages, rather than clay. By increasing the PACl dosage, more coagulant is being added into the filter column. Overall, an increase of mass accumulated within the pore would result in a smaller pore size and an overall greater head loss.

The head loss curves were also normalized for the mass of PACl in the filter which revealed that head loss is more dependent on the concentration of PACl dosages added rather than the amount of clay.

The density of the flocs were then calculated and compared in order to account for why the head loss was much at higher PACl dosages. It was found that the density was lower for higher PACl dosages due to the possibility that they contain a larger ratio of water to clay. This proved to reaffirm the "fractal behavior" theory. However, these calculations and conclusions do not necessary disprove the other two theories. In fact, the three seem to be at least in some sort of way interdependent of one another. While this statement of interdependency and its extent cannot be completely confirmed, still more tests need to be done to complete a mathematical model for the filter performance.

Future Work

Over the course of this semester, a number of solid experimental trials were run and evaluated at varying PACl dosages (0.2 mg/L, 0.65 mg/L, and 1.1 mg/L). From this data, new conclusions and progress towards formulating a relationship between mass accumulation and head loss with the filter column were made. However, because of a number of laboratory and experimental problems as well as a major hypothesis alteration, a concrete mathematical model was not yet completed. Because of this, future SRSF Theory sub-teams should use research derived from this semester to continue to explore the possibilities of creating a mathematical model that can relate the mass of clay that can fill a pore before no more particles attach and how this value depends on PACl dosage.

In addition, experimental data from trials run this semester has proven that head loss continues to increase linearly even after filter failure. This unusual trend contradicted the original hypothesis that stated that head loss would level off. In some tests, head loss values reached values well beyond expected values, upwards of 300 and 400 cm. While three theories were proposed this semester to explain this phenomenon, more experimental testing and research should be undergone to prove or disprove these theories.

Team Reflections

During this semester, a number of systematic problems with our experimental set-up were corrected for. For instance, during one week a leak in our set-up was identified, and an old connector was replaced to stop air bubbles from entering and water drainage of the sand filter during experimental trials. During another week, tubing was replaced between the clay stock tank and influent turbidity meter to prevent the clogging of clay and the irreversible drop in incoming influent water turbidity. Although dealing with these problems did delay experimental testing by several weeks, these new corrections should improve experimental testing in the future.

Because of the delay in experimentation, progress in developing a mathematical model were not as to the extent that we would have liked. However, through the works of developing the model, progress was made to correct original hypotheses about the trends of head loss after filter failure. From this, new hypotheses and theories were developed to explain observed trends in head loss and attempts to prove each theory are currently underway. These new theories could help to create the mathematical model in future semesters and help to explain the happenings within the filter column.

References

[1] "what is pid? tutorialoverview.", 08 Nov. 2013.

[2] Practical Actions. Slow sand water filtration, 1999.

[3] Michael J. Adelman, Monroe L. Weber-Shirk, Anderson N. Cordero, Sara L. Coffey, William J. Maher, Dylan Guelig, Jeffrey C. Will, Sarah C. Stodter, Matthew W. Hurst, and Leonard W. Lion. Stacked filters: Novel approach to rapid sand filtration. 138:999–1004, 2012.

[4] Theresa et al Chu. Research report summer 2013, 6 August 2013.