Summer 2014 Report

Richa Gwalani, Guneet Sandhu, Tom Schultz and Savannah Wing

August 1, 2014

1 Introduction

People in many parts of the world are still devoid of basic human necessity like clean drinking water. Many drinking water treatment systems in the global south face limited economic viability because of the unreliable source of electricity and expensive operation costs. Stacked Rapid Sand Filters (SRSF) were invented by the AguaClara team to eliminate the need for pumps or control equipment, thus making it more robust and reliable than conventional rapid sand filters. The low-flow stacked rapid sand filter (LFSRSF) is an adaptation of the SRSF for flow rates < 3.0 L/s and is currently being deployed in India for flow rates of 0.8 L/s serving communities of about 500 people. The previous LFSRSF research teams have been working on fabricating the laboratory version (version 1) of the filter with continuous improvements to the design aimed at simplifying the operation and maintenance of the filters. This version of the full-scale filter in the lab fabricated by the previous team has 0.2mm slotted pipes throughout and top and bottom manifolds consisting of single slotted pipes. The inital version 1 filter is nearing completion in two villages in India, Rohne and Gufu.

Our work was to fabricate the next version full-scale filter, version 2, which was built upon the previous teams version 1 filter. In the 2nd version of the full-scale filter, we tried to mitigate problems faced by the previous version, such as overflowing of the inlet tank and the inability to backwash at designed flow rates. We also wanted to move towards the ability to handle and filter turbid water. This 2nd version of the full-scale LFSRSF will be used as a prototype for mass production by the Tata Water Mission in India. A major part of optimizing the operation of the filters included accounting for head loss incurred in the system and incorporating these changes in the final design of the critical components of the filter.

2 Literature Review

2.1 Low Flow Stacked Rapid Sand Filter Spring 2014 Report

The report from Spring 2014 includes the construction processes involved in fabricating the filter and all associated components. The report also includes design specifications for the slotted manifold, trunks, plumbing systems and sand for the filter. The report includes documentation regarding the operation of the filter for filtration and backwash mode along with the design of the unique flexible-tubing derived sand drain. However, the report also outlines issues that need to be dealt with: the current filter cannot handle backwash flow rates greater than around 0.6 L/s, suggesting that the entrance and exit tanks need to be raised, and the report also documents larger-than-expected head loss during backwash, the source of which needs to be investigated. The sand drain although designed needs to be tested/improved for ease of operation. It is also desired to have an ease of transition between the filtration and backwash mode which will require designing the pipe stubs to proper heights. The previous team installed pressure sensors on the filter column to collect data to evaluate the flow distribution in various sand layers.

2.2 "Novel Fluid Control System for Stacked Rapid Sand Filters" and "Stacked Filters: Novel Approach to Rapid Sand Filtration"

In order to gain a better understanding regarding the stacked rapid filter in terms of design and operation, the above mentioned papers were referred. These papers, published in the Journal of Environmental Engineering in 2013 and 2012 respectively (corresponding author: Monroe Weber-Shirk) describe the operation of an AguaClara Stacked Rapid Sand Filter (SRSF) and the fluidic controls it employs when switching between filtration and backwash. The papers propose that stacking a sand filter as opposed to laying it out horizontally is an effective and novel way to filter water thus occupying less space. This compact system can address the limitations of conventional rapid sand filtration for different water systems across the globe. The system can backwash at the same flow it inlets in, and does not require traditional pumps driven by electricity. There are numerous challenges faced when dealing with water filtration and clean water solutions. The Low Flow Stacked Rapid Sand Filtration seeks to build off the conventional rapid sand filtration units and help ease the use and maintenance of sand filtration units. A pilot system was built here at Cornell University, and experimental tests suggest that these units would indeed be effective in the field. The tests show that there is a five zone transition between filtration and backwash using the fluidic control system. The fluidic control is based on a siphon system controlled by an air valve, and on water level changes that are designed into the system. This system will make it much more effective than traditional sand filters. The LFSRSF is a closed column, unlike the SRSF that is open to the atmosphere, and does not use the siphon system in use in the SRSF. However, like the SRSF, flow in and out of the filter is controlled by the placement (height) of each inlet entrance and outlet box. These heights are governed by differential pressure and head losses. The calculations done for the SRSF configuration will aid in the modifications necessary to eliminate some of the excess valves of the LFSRSFs being built in India, and assist in the development of a simplified way to initiate backwash.

2.3 Fluid Mechanics, 7th edition by Frank M. White

This textbook offers basic information on fluid mechanics theory and application. In reference to our project, chapters on pressure distribution in fluids, pipe flow, and flow through porous media are especially important.

2.4 Lecture Slides, CEE 4540, Sustainable Municipal Drinking Water Treatment, Monroe-Weber Shirk, Cornell University

A portion of these slides discuss AguaClara SRSF technology, and many of the mechanisms mentioned in the paper above. The Karman-Kozeny equation, the rationale for using 6 filter layers of a depth of 20 cm., and the relation of pipe stub heights in the inlet and exit tanks to filtration and backwash modes is well explained in these slides: all of these are critical elements to the LFSRSF as well therefore can be adapted from the SRSF conceptually. In order to analyze the data, key fundamentals of fluid mechanics were discussed in the lecture slides as well.

3 Experimental Design

One of the major issues that the LFSRSF team faced in the last semester was an unexpected high head loss during backwash that made it impossible to achieve the design upflow velocity of 11 mm/s. It was suspected that the head loss through the slots was higher than predicted. One of the major tasks assigned to the Summer 2014 LFSRSF team was to investigate the source of the head loss by testing inlet plumbing losses, losses through the sand bed, and losses through the slotted pipes. It was therefore desired to measure the head loss through a slotted pipe manifold system as a function of flow rate and compare with theoretical models used in the LFSRSF design code.

Using a small-scale two tank set up, the head loss through the slotted pipes with and without sand was measured by pressure sensors placed on the two tanks. It was also realized that in order to interpret observations as accurately as possible for the full-scale filter, the experimental system should closely resemble the actual arrangement of the slotted pipe in the filter. A Mathcad sheet was created to process the raw data from the pressure sensors and to estimate head loss through the slotted pipes both with and without sand.

	Measurements
Inlet Plumbing Head Loss	18 cm
Overall Head Loss	31 cm

Table 1: Head Loss measurements

3.1 Head Loss Measurements in the Filter

In order to measure the head loss through the initial filter version 1, the team operated the filter in filtration mode. At the designed flow rate of 0.8 L/s, we measured the inlet plumbing head loss in the system by measuring the difference in the water level height between the sand drain manometer and the entrance tank of the filter. The overall head loss was measured by measuring the difference in the water level height between the entrance and the exit tanks.

Mathcad code was used to predict the inlet plumbing and overall head loss. As one can see from the table above, the inlet plumbing head loss during filtration mode which includes the slotted pipes was 18 cm while the code predicted a value of 8 cm. The overall head loss was found to be 31 cm, while the code predicted a value of 21 cm. We clearly saw huge difference between the head loss predicted by the design code and the values that were measured experimentally.

The backwash mode was initiated and the head loss was measured again using the same techniques. The entrance tank flooded at the design flow rate and the flow rate was reduced to 0.4 L/s. At a flow rate of 0.4 L/s the inlet plumbing head loss was measured to be 148 cm. These results together suggested that we needed to change our system in order to lower head losses and to run our system at designed flow rate.

3.2 Evolution of Small-Scale Experimental Setup

The experimental setup went through many design iterations as depicted in Figure 1. We wanted to mimic the actual slotted pipes in the full-scale set up as closely as possible, while attempting to solve the issues regarding head loss in pipes and sand bed. The design went from hard PVC piping (model-1) to flexible tubing (model-2), and the team decided to move towards a horizontal system (model-3) instead of a vertical system. Initially in using the Mathcad code, we saw that the values changed drastically with a change in elevation between the entrance and the exit tank. The team decided to remove this element of elevation. However, in the end we found that it was not this change in elevation but a problem with the extrapolation of the curve in Mathcad that was causing a problem. The extrapolation of the curve is dicussed later in the report. Still, we kept with the horizontal set-up becuase it was easier to handle. Based on the data collected and analyzed for these set-ups, the team concluded to redesign the two bucket system again to the current setup which includes two PVC pipes (12 inch as source tank and 6 inch as exit tank) as tanks.

The crux of the setup was to submerge a single slotted pipe in a tank of water and connect the tank with the slotted pipe to a second tank that serves

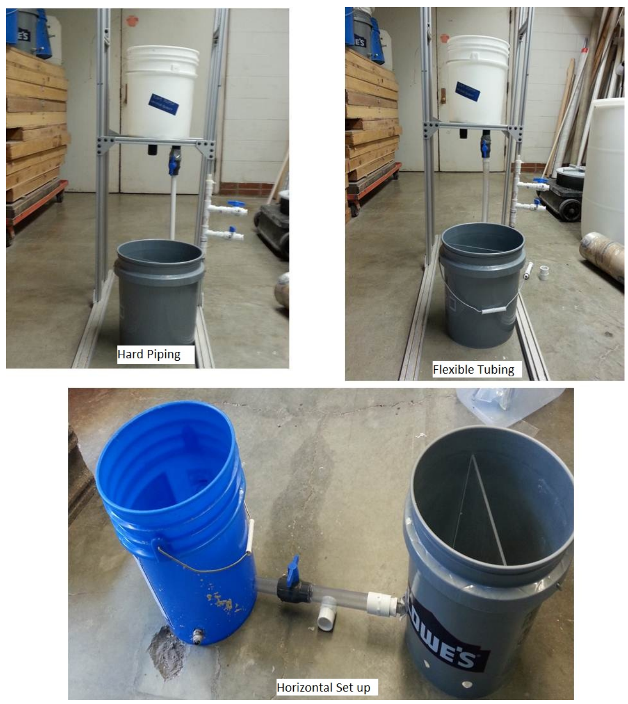

Figure 1: Evolution of the Experimental Setup

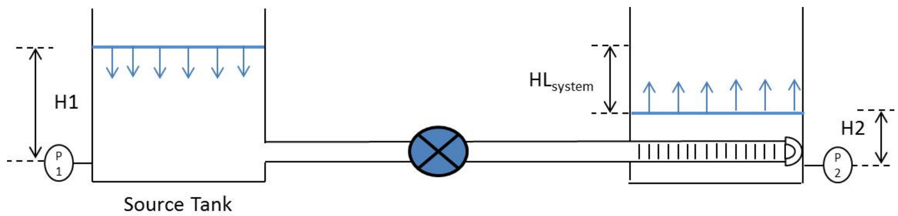

Figure 2: Experimental Setup to Determine Head Loss Through Slotted Pipe covered with Sand

as a supply. Using pressure sensors connected to each tank, the pressure in the tanks was recorded. The two sensors provided enough information to track both the difference in elevation between the two tanks and thus the head losses as well as the rate of change of depth in the tanks which can be used to measure the flow rate. The system is described by Figure 3.2 below;$Q = \frac{dH1}{dt} A_{Tank}$ where Q is the flow rate, H1 is the water level in source tank and A_{Tank} is the cross sectional area of the source tank.

Data was collected for three different experiments: no sand and without slotted pipe, slotted pipe without sand, and slotted pipe with sand. Each system had to go through various leak tests along with the calibration of the pressure sensors. The calibration of the pressure sensors was done after we zeroed it at a certain marked base line water level. Then by changing the water level in each tank (entrance and exit), we measured the height of the water level from the base line with the help of measuring tape. Finally, we compared this measured value with that of the converted pressure to height value from the Mathcad design code and pressure sensors.

The pipe and valve connecting the two tanks was designed in such a way that head loss through the connection is small. In order for the head loss through the slotted pipes to dominate, it was decided to opt for a smaller section of the slotted pipe with about 15 slots on each side. However, by running this system, the team realized the sand bed was not entirely fludizied because the length of the slotted pipe was too short in comparison to the diameter of the bucket. This lead to erroneous estimation of head loss using the Karmen Kozeny equation which considers the velocity through the entire sand bed. It was therefore more conducive to have the system resemble as closely to the dimensions of the slotted pipe as possible. In order to obtain more accurate estimation of the head loss through the sand bed, it was decided to measure the head loss across the sand bed using a pressure sensor that calculates the difference between the pressure at the top and bottom of the bed. We deemed this a better option than inferring from the measured data using data analysis techniques in Mathcad.

Upon analyzing the data from the previous versions of the set up, some key conclusions were drawn that led to the refinement of the experiment and the ability to obtain quality information. This information can be used to make key decisions prior to testing under turbid conditions.

1. The head loss owing to plumbing losses was measured by running the small-scale model-3 without the slotted pipe attached. Then the experimentally determined piping head loss was subtracted from the total measured head loss to get the head loss through the slotted pipe for the same flow rate. The measured results were compared with the orifice equation prediction for the slotted pipes consistent with the design code used to design the slotted pipes and the filter in general. In order to assess the influence of the sand bed, data from Experiment 1 (only slotted pipe and no sand) was analyzed and the head loss was compared to the theoretical orifice equation and the head loss incurred by the system with sand.

2. In order to trace the head loss by virtue of the slots covered with sand, the plumbing head loss of the system should be minimized such that the head loss through the slotted pipes dominate. In order to do the same, pipe fittings and long connecting pipes should be minimized.

3. The raw data obtained was very noisy owing to fluctuations in the system or voltage in the pressure sensors. In order to mitigate this issue, the raw data was fit by utilizing curve fitting techniques in Mathcad where the raw pressure data was fit with time using polynomial regression of order 2.

4. Upon analyzing the data obtained from the previous experimental set up, it was evident that the head loss through the slotted pipes observed experimentally was not in agreement with the orifice equation used to calculate the head loss through the slots theoretically in the design code. Once again by using polynomial regression of order 2 for pressure and flow rate, the coefficients of the curve fitting equation yielded information regarding the variation or deviation of head loss from expected/ theoretical models. The team wanted to obtain a model based on experimental observations that could translate into a correction factor that can be used in the design code to obtain correct head loss/slotted area for better and more accurate designs.

3.3 Current Setup

Based on the key findings from previous setups and after analyzing the data and results obtained, the team refined the small-scale set up as depicted in Figure (model-4) 3.

In the current setup, the supply tank which is a 12 inch PVC pipe was sealed at the bottom with a cap and weir that acted as a drain in the tank. The team decided to keep a constant flow rate through the system by maintaining a constant head. In order to have a fixed flow rate, the water level in the entrance tank was marked upon the start of the experiment and then the valve connecting the two tanks was opened. Three different marking of the water level were made to have the same flow rate for each of the three different experiment (no sand without slotted pipe, slotted pipe without sand and slotted pipe with

Figure 3: Apparatus to measure component head loss.

sand). The same flow rate will be used in all three experiments by adjusting the water level in the supply tank. By doing this we tried to run the three different experiment in the same flow rate range for the ease of comparison and to remove the extrapolation errors which we were getting in section 3.2.

In order to mitigate the issue of measuring incorrect elevations, it was ensured that the entrance tank and the exit tank pressure sensors are zeroed at the same water level. The exit tank was a 6 inch PVC pipe with a sealed bottom, so that the diameter was comparable to the length of the slotted pipe that was housed inside. A dummy slotted pipe was also glued in above the main slotted pipe to mimic the presence of slotted pipes in the upper manifold as seen in Figure 4. The dummy slotted pipe was used only to account for the influence of slotted pipes in upper layer on the fluidization of the bed. The same small scale set-up was used in determining the head loss through the slots and the minimum head required to fluidize the bed.

The team faced a problem in keeping the pressure sensors dry during the experimental runs. We decided to use longer connecting tubes to keep the pressure sensors as far away from the tanks as possible. We also taped the tubes connecting the pressure sensors down to the exterior of the kiddie pool to ensure that the sensors would remain in a dry place. The team was then able to get good and consistent pressure data points for analysis. The experiment was first run in the filtration mode (no fluidization) and then run for backwash (fluidization) scenarios.

One of the issues that the team faced during the backwash runs was the high flow rates needed to initiate backwash. There were many inconsistent observations during the fluidization of the sand bed. Depending upon the the length of time that the sand had to sit, the bed would fluidize at different pressure head. The more time that we let the bed sit, the better the sand would fluidize in the next run. Often times the first run of the morning after a night

Figure 4: The Exit Tank with Slotted Pipe for Experimental Runs with and without Sand

of no activity proved to be the most fluidized run. Once the bed was fluidized and then let to settle, the next run would require a higher flow rate and thus more loss was present in the system. Given the limited height of the exit tank and in order to provide necessary flow without the risk of overflowing, the team decided to reduce the sand bed height to 14 cm from 20 cm. During analysis, the head loss was corrected analytically for 20 cm in order to be consistent. The issues that the team faced with fluidization are similar to the sand bed collapse issues associated with backwash on field. This test may prove that the sand is fluidizing by its stratified layers, and that collapse is possible if water cannot sufficiently hold the different layers up as it moves up the column in the full-scale model.

3.3.1 Some Key Findings:

1. The team ran the experiment for the slotted pipe-no sand experiment and no slotted pipe-no sand experiment. The results seem to follow the correct trend. Upon running the slotted pipe-sand run, the head loss through the sand bed was observed to be very high, which caused the head loss through the slotted pipe to be lower than expected. It could be by virtue of incorrect data obtained or incorrect modeling. The team has to further investigate the cause of this deviation. Upon further discussion, the team realized that the turbulent interaction of the sand bed with the slotted pipe should be differentiated from the head loss through the bed. In order to do that, the experiment with no slotted pipes-no sand will be modified to no slotted pipes-sand, to account for the head loss through the sand bed alone.

2. After running the experiment again and managing to keep the pressure sensors dry, the data obtained was much more convincing and the results were much more in line with expectations. Regarding the sand bed head loss, after consulting with Professor Weber-Shirk, it was decided that the sand bed head loss can be obtained analytically from the head loss equation by taking the coefficient of the linear flow rate. As head loss through a sand bed by Karmen-Kozeny equation also varies linearly with the flow rate, the same concept is used to obtain the sand bed head loss in the analysis instead of determining the head loss experimentally as planned previously using the entrance with the mesh (the mesh will act as a major source of head loss).

3. One of the major conclusions in the analysis based on the experimental runs was a correction factor for the area of slots that accounts for the deviation between the predicted and obtained head loss. In the AguaClara design code for the backwash mode, the slots are designed as per the orifice equation for no coverage assuming during fluidization there will be no slot coverage. However, during backwash initiation, the slots are covered with sand and this should be a constraint for design. As per the analysis, $HL = \frac{K*Q^2}{Area^2*2g}$, where K is the minor loss coefficient and Q is the flow

rate. For the orifice equation if the coefficient of Q^2 is isolated we get $K_{Predicted} = \frac{1}{2g*(Area_{SlotsEffective}*(1-coverage)*Pi_{VenaContractaOrifice})^2}$. For the K value obtained experimentally, the coefficient of $Q^2$is determined by curve fitting. Upon comparing the K values of the theoretical (design code) and experimental analysis, a correction factor for the area was determined to be 2, which implies that the area of the double side slotted pipes should be 2 times greater than the existing area. Using this correction factor, the predicted or theoretical value of head loss converges with the experimentally determined value. This also implies that the slots are 50% covered during backwash initiation that the design code does not account for.

3.4 Sand Drain Testing

For the small-scale horizontal model previously discussed, more sand was required than available to obtain a 20 cm sand layer in the exit tank. The team decided to obtain sand from the filter and therefore test the sand drain. Originally, the team thought that putting the full-scale filter into backwash mode while forcing all the water through the sand drain would force the sand out of the filter easily. What we saw in practice was that this system was insufficient and required the user to massage the tube heavily. We came to the conclusion that we could not force enough water through this pipe because we could not yet hit designed flow rates. Therefore, we decided to run the filter in filtration mode and close all the exits, thus forcing the water again through the sand drain but with the 0.8 L/s designed flow rate. The process took about a minute to begin, but once the sand started to drain out of the tube it flowed perfectly and the entire system could drain between 5-10 minutes. This new sand drain method should be tested at the full scale SRSF filters in Honduras. We are still unsure of the possibility of sand removal during backwash mode now that we can run at 0.8 L/s, but we nonetheless have an option that works efficiently.

After talking to Maysoon Sharif and comparing results to the field filters, we concluded that the top and bottom manifolds on the field consisted of double slotted pipe and our version 1 lab filter had single slotted pipes. She told us that field filters were backwashing but it took 20 minutes to initiate the process. As we were facing problem with the backwash, we decided to change the bottom manifold slotted pipes to be consistent with field filters. As the problem of draining the sand was solved by running it in filtration mode we were able to drain out all the sand and replace the bottom manifold with double slotted pipes from the middle manifold. Upon testing the full-scale filter in backwash mode, the team noticed that filter could handle 0.65 L/s of flow rate which was a sign of improvement. The team decided that 0.3 mm slotted pipes would be a better solution and we would be able to run the filter at the designed flow rate.

Upon receiving the 0.3 mm slotted pipes, the filter once again had to be drained to replace the slotted pipes and the team ran the filter in filtration mode with all inlets open for the sand drain operation. The sand drain worked

Figure 5: Sand Drain Testing : Filtration Mode with all inlets open and the exit shut off

successfully again as depicted in Figure 5. The effects of the redesign are discussed in section 3.5.

3.5 Slotted Pipe Redesign

Maysoon Sharif, AguaClara LLC, explained that the LFSRSF design used in the villages of Gufu and Ronhe have slotted pipes with the same slot area and configuration for all 7 inlets and outlets including the backwash and top inlet manifold. The laboratory filter slotted area in the backwash and top inlet manifold was half the slotted area of the middle manifolds as recommended by the AguaClara design code. In an attempt to reduce the head loss through the system, two recommendations were made by Professor Monroe Weber-Shirk:

1. Increase the backwash slots by a factor of 2 and make those slots the same as the double flow inlet and outlets will decrease head loss by a factor of 4.

2. Further reduction in head loss through the slots can be obtained by increasing the width of the slotted pipes from 0.2 mm to 0.3 mm. As the effective size of sand is 0.45 mm, increasing the slot size to 0.3 mm would not be a bad choice. Increasing slot size from 0.2 mm to 0.3 mm and

doubling the number of slots for the backwash will increase the slot area by a factor of 3 and reduce head loss by a factor of 9.

Based on the above recommendations, the team decided to order both 0.2 mm (for the backwash and top inlet manifold) and 0.3 mm (for the entire filter) slotted pipes for the filter with an aim to measure any improvements to the system with both alternatives. Given the time constraints, the team decided to keep the slotted pipe branch spacing on the manifold the same, so that the existing manifolds could be used for testing and analysis.

While waiting for the order of the slotted pipes to arrive, as suggested by Professor Weber-Shirk, the backwash slotted pipes were replaced with double side slotted pipes from one of the middle manifolds. This was done so that the team could run the filter and see improvements in the operation immediately just by switching to double sided slotted pipes for backwash. The team then drained the filter sand as described in section 3.4 and dismantled it in order to gain access to the manifolds. The team replaced the single sided slotted pipes of the backwash manifold with the double slotted pipes of the top most exit manifold. Upon removing the slotted pipes, the team also observed fouling and entrained sand particles in the slotted pipes as depicted in Figure 6 which was more pronounced in the single sided slotted pipe than the double sided. Since there is no flushing mechanism in the current laboratory setup, fouling inside the slotted pipes can be a potential failure mode.

After replacing the bottom manifold with the double slotted pipe of 0.2 mm slotted pipes, the team filled the filter with sand and reassembled the filter. During the backwash mode, the flow rate was increased to 0.65 L/s without the entrance tank flooding. This is higher than the previous maximum backwash flow rate of 0.4 L/s. The head loss measured (difference between the entrance tank water level and the sand drain water level) also reduced to 100 cm as compared 148 cm as reported in section 3.1. However, the team kept in mind the suggestion of first fluidizing the bed by layers and then pushing all of the water through the backwash inlet. When backwashed by layers, the team observed that all the inlets except the backwash inlet were operating in backwash mode at 0.8 L/s but the backwash inlet operated at this lower flow rate of 0.65 L/s. Although replacing the slotted pipe did improve the performance, the team suspects some design flaw in the backwash manifold which inhibits the backwash operation at design flow rates.

Upon receiving the 0.3 mm slotted pipes, the team once again replaced the slotted pipes. The bottom manifold was switched to 0.3 mm double slotted pipes and the top manifold was switched to 0.2 mm double slotted pipes. The 0.2 mm slotted pipes used for the previous measurement (backwash as described above) were placed back to their previous location in the middle manifold. The new pipes were cut and milled according to the existing pipe dimensions. After replacing the slotted pipes, the team faced some issues with sealing the filter, which caused delays in running the system and testing the new slotted pipes.

The issues with sealing the filter primarily arose due to the incorrect placement of the gasket and the fact that due to repeated opening and closing of

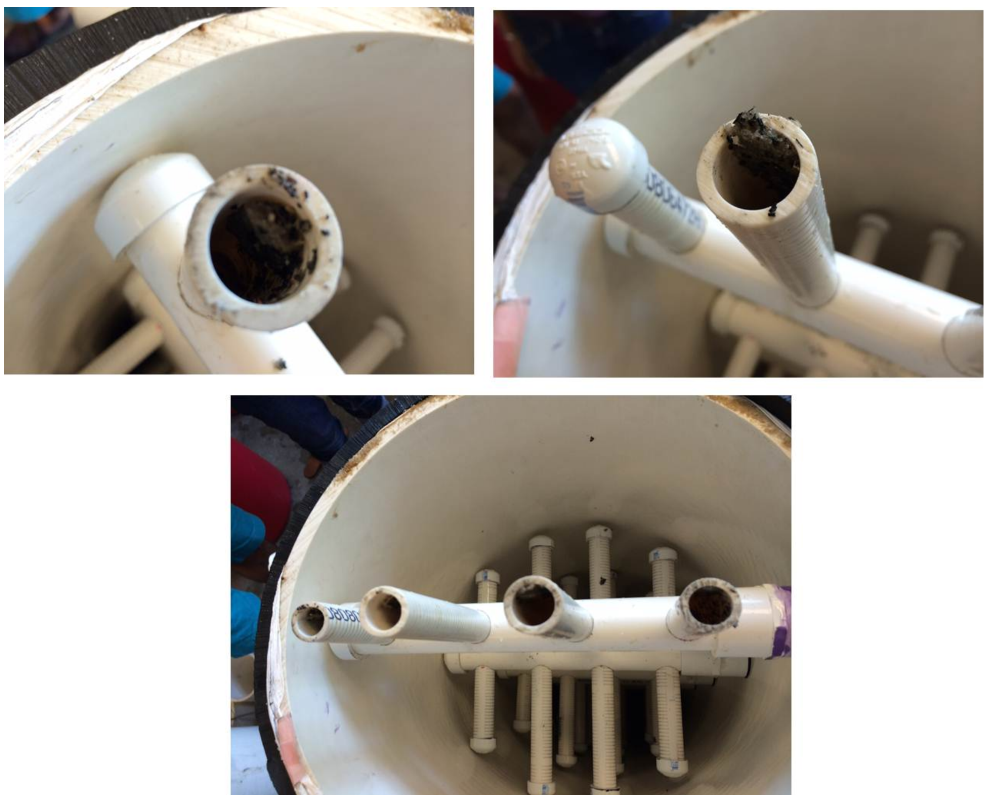

Figure 6: Fouled Slotted Pipes of the top inlet

	Inlet Plumbing Head Loss	Overall Head Loss	Slot Size (top)	Slot Size (bottom)
Run 1 (old pipe stubs)	18 cm	31 cm	0.2 mm, single	0.2 mm, single
Run 2 (old pipe stubs)	7 cm	41.5 cm	0.2 mm, double	0.3 mm, double
Run 3 (no pipe stubs)	6.5 cm	29 cm	0.2 mm, double	0.3 mm, double
Run 4 (murky water/new stubs)	11.5 cm	48 cm	0.2 mm, double	0.3 mm, double
Run 5 (murky water/new stubs)	10.5 cm	32.5 cm	0.2 mm, double	0.3 mm, double
Run 6 (pipe stubs reversed)	7.5 cm	27 cm	0.2 mm, double	0.3 mm, double
Run 7 (after 4 days)	9 cm	29 cm	0.2 mm, double	0.3 mm, double

Table 2: Data for Filtration Mode (flow rate used is 0.8 L/s for all the runs)

the hose clamps, the bolt heads were deformed. This caused problems when the bolts were tightened using the torque wrench. The problem was mitigated by replacing the clamps and aligning the filter sections more carefully before putting the gasket on. The grip of the gasket should be tightened to 40 in-lbs and it should be ensured that the hose clamps are aligned on the joint of the two sections. Another problem that the team faced was keeping the PVC cap on top of the filter intact. Everytime the team would try to run the filter, the cap would come off. However, it was soon realized that the issue was due to the trapped air in the filter. It should be ensured that the exit is not plugged during the trial runs for water tightness. Upon correcting this problem, the filter was water-tight barring some minor leaks at the connections which were corrected using silica gel and teflon tape.

Resolving the sealing issues with the filter, the team proceeded to run the filter for both the filtration and backwash mode. We were tasked with measuring the headlosses and determine the most efficient way of transitioning between filtration and backwash, including what heights of weirs, if any, were needed in the inlet and outlet pipes.

We tried different run on full-scale filer. Firstly, we ran the filter as an initial design with single slotted pipe at the top and the bottom of the manifolds. Secondly, we changed the bottom manifold with 0.2 mm double slotted pipe for the backwash run. Thirdly, we ran the filter with the double slotted top and bottom manifolds. The top manifold had a 0.2 mm slot size and the bottom manifold had a 0.3 mm slot size. All the following runs were done with the doubled slotted pipe at the top and bottom manifold with a 0.2mm slot size everywhere except the 0.3 mm slot size on the bottom manifold. Forthly, we introduced some murky water which we prepared by adding some mud from outside into water and leaving it for a day. Fifthly, we removed all the pipe stubs from the inlet tank. Sixthly, the pipe stubs were added to the inlet tank, the shortest size being 12 inches, middle being 45 cm and longest being 56.5 cm. The pipe stub order was reversed for the measurement where the shortest pipe served the 1st manifold and so on. All of the findings and measurements are tabulated below for reference.

	Inlet Plumbing Head Loss	Flow Rate	Slot Size at top	Slot Size at bottom
Run 1 (old pipe stubs)	148 cm	0.4 L/s	0.2 mm, single	0.2 mm, single
Run 2 (old pipe stubs)	100 cm	0.65 L/s	0.2 mm, single	0.2 mm, double
Run 3 (old pipe stubs)	39 cm	0.8 L/s	0.2 mm, double	0.3 mm, double
Run 4 (old pipe stubs)	46 cm	0.8 L/s	0.2 mm, double	0.3 mm, double
Run 5 (murky water/new stubs)	48 cm	0.8 L/s	0.2 mm, double	0.3 mm, double
Run 6 (murky water/new stubs)	66 cm	0.8 L/s	0.2 mm, double	0.3 mm, double
Run 7 (pipe stubs reversed)	58 cm	0.8 L/s	0.2 mm, double	0.3 mm, double

Table 3: Data for Backwash Mode

4 Filter Performance Testing

After measuring a more consistent head loss and successfully getting the filter to switch back and forth between filtration and backwash modes with only the use of one valve, (after the first tranisition to backwash, in which the air was removed from the top of the filter and from the backwash siphon) it was decided to move forward and test the filter's performance and failure modes using turbid water with coagulant dosing. The aim of these tests was to find out how much the head loss will increase for both filtration and backwash modes when the sand bed is dirty, and whether the filter would be able to backwash with our current system (0.8 L/sec and no removal of the stubs during backwash) when it is clogged.

4.1 Experimental Setup

Upon suggestion from Professor Monroe Weber-Shirk, the team decided to run the filter with very high turbidity in a coagulant-dosed water (500 NTU with 20 mg/L of PACl). Given the theoretical filter performance of 50 NTU hours, 500 NTU influent would give a clogging time for the filter of 6 minutes which was deemed a manageable run time, and 20 mg/L of PACl was suggested as a corresponding coagulant dose. The flow rates needed to achieve these dosages for the filter flow rate of 0.8 L/s were then calculated to be 544 mL/min for the raw clay water, given a concentration of 75 gm/L and 15.31 mL/min for the coagulant, using the stock concentration of 62.7 gm/L.

The calculations for the above numbers is as follows and the link for the same is: X:\RESEARCH\Low Flow Stacked Rapid Sand Filtration\Summer 2014\Pictures\math.JPG

A tubing size of 17 was to be used for the pumps, therefore a 600 rpm pump set to 192 rpm for the clay and 100 rpm pump set to 5.5 rpm for the coagulant was needed.

A member of the Summer 2013 LFSRSF team was consulted and said that in order to clog their filter, they had to run it at 500 NTU for around 40 minutes to get it to clog completely. Therefore, a 5 gal bucket was used for the clay to

Raw water

$$500\text{NTU} = 0.85\cdot\frac{\text{gm}}{\text{L}}$$

$$a := \frac{0.8\,\frac{\text{L}}{\text{s}}\cdot 500\text{NTU}}{75\,\frac{\text{gm}}{\text{L}}} = 544\cdot\frac{\text{mL}}{\text{min}}$$

$$\frac{5\text{gal}}{a} = 34.792\cdot\text{min}$$

$$5\text{gal}\cdot 75\,\frac{\text{gm}}{\text{L}} = 1.42\,\text{kg}$$

Coagulant

$$\frac{0.8\,\frac{\text{L}}{\text{s}}\cdot 20\,\frac{\text{mg}}{\text{L}}}{62.7\,\frac{\text{gm}}{\text{L}}} = 15.311\cdot\frac{\text{mL}}{\text{min}}$$

$$15.311\,\frac{\text{mL}}{\text{min}} + 544\,\frac{\text{mL}}{\text{min}} + 0.8\,\frac{\text{L}}{\text{s}} = 0.809\cdot\frac{\text{L}}{\text{s}}$$

$$15.311\,\frac{\text{mL}}{\text{min}}\cdot 34.792\text{min} = 0.533\,\text{L}$$

diluting coagulant for 60 rpm(168mL/min)

$$\frac{0.8\,\frac{\text{L}}{\text{s}}\cdot 20\,\frac{\text{mg}}{\text{L}}}{168\,\frac{\text{mL}}{\text{min}}} = 5.714\cdot\frac{\text{gm}}{\text{L}}$$

$$\frac{5.714}{62.7} = 0.091$$

$$\frac{1\text{L}}{168\,\frac{\text{mL}}{\text{min}}} = 5.952\cdot\text{min}$$

$$34.792\text{min}\cdot 168\,\frac{\text{mL}}{\text{min}} = 5.845\,\text{L}$$

Figure 7: Math Calculations

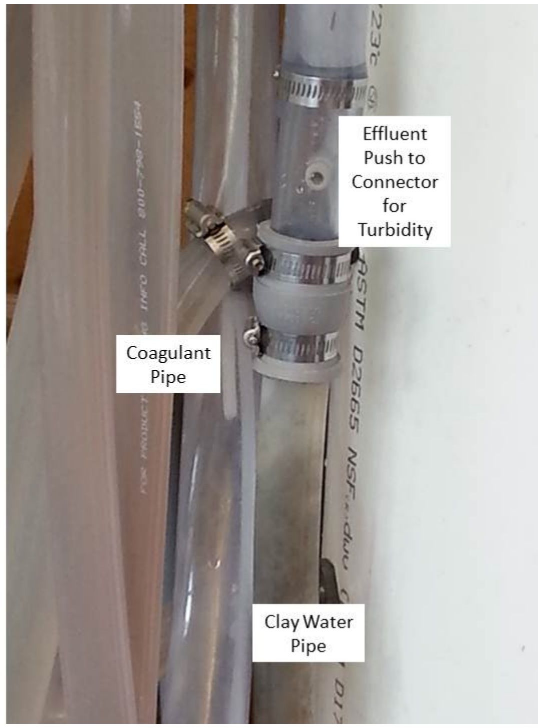

Figure 8: Clay and Coagulant into Influent water

give a run time of about 35 minutes. Correspondingly, 0.533 L of coagulant was needed. To dose the influent water of the tank, the clay and coagulant piping was introduced into the influent by cathetering the entrance tank flexible tubing that draws clean water from the filter pump to the entrance tank. The clay tube was placed further down than the coagulant tube to ensure proper mixing of the clay first with water, and then the mixture would get dosed with coagulant. In order to maintain a constant concentration of raw water, a stirrer would need to be placed in the 5 gallon bucket with the clay mixture. At the time of setup there were no available functioning stirrers so an order was placed for new ones, however the team stirred using a large rod for the first few runs.

Two turbidimeters and another 100 rpm pump were used to measure the turbidity of the water. Influent and effluent water samples were obtained by inserting a section of hard tubing in the entrance and exit tank flexible tubing. The water for the influent turbidimeter was obtained from a push-to-connect inserted in the hard tubing into the entrance tank. The clay and coagulant pipes were carefully placed far enough down from the turbidimeter push to connect to ensure an accurate reading. Similarly, the effluent turbidimeter obtained water from a push-to-connect attached to the hard tubing section in the exit tank's flexible tube. The effluent water of the turbidimeters was then pumped into a

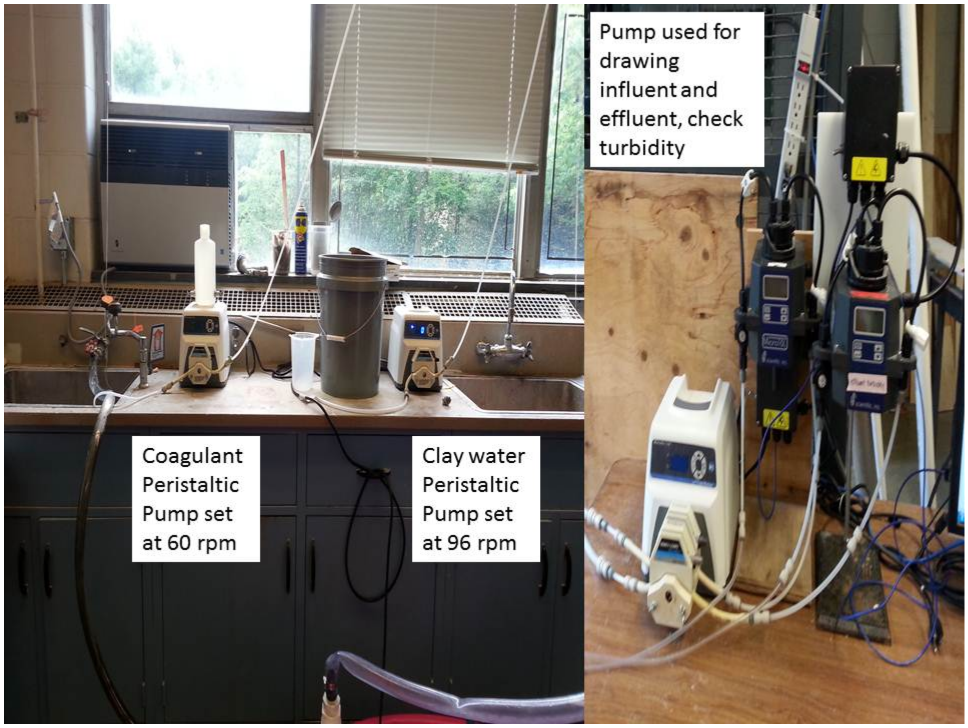

Figure 9: Set-up for the Coagulant and Clay alongwith Turbidimeters

sink.

4.1.1 Refining the Original Setup

After the first two runs were conducted, several issues were apparent with the original setup for the filter performance testing. A major issue we faced was with the coordination of getting water into and out of the filter. One problem was that in adding a section of hard pipe to the flexible influent tubing, a slighlty larger section of flexible tubing had to be used to connect the filter pump to the entrance tank. This flexible tubing had many kinks in it, and had to be held up to maintain a 0.8 L/s flow rate. This meant that some one had to hold up the tubing while also making sure that enough water was flowing from the sink into the bucket that held the pump. Another problem was that since there was no stirrer for the clay mixture, someone else had to continually stir the mixture manually to keep the clay suspended. There was also an issue in removing water at a fast enough pace so that the pool holding the filter and catching the effluent water would not overflow. A pump is placed in the pool to remove water, but it was not powerful enough to remove it as fast as it came out. During filtration, the exit tubing could be placed in the sink as well, however the sink would start to overflow after a few moments. We suspected that there was an issue with the draining of the lab sinks. Hence, the test runs could only last as long as the water was not going to overflow.

The other issue we found was that the turbidimeters were getting quickly maxed out at 1100 and 110 NTU for the influent and effluent respectively. One problem we found was that the coagulant was not actually flowing as it was supposed to. After all the air bubbles were removed from the coagulant tubing and the flow was started, it was found that the pump was unable to maintain a consistent flow of coagulant because we did not connect the tubing between the PACl bottle and the pump up properly. On the second run the other issue was that the clay mixture was not properly stirred, so that the clay was settling and increasing the influent turbidity.

Before running any more tests, the filter was run in filtration and backwash modes with only clean water several times to clear all the tubing and clean the sand bed. Then we situated the filter pump and holstered the tubing by taping it to the filter so that it no longer had to be held up to control the kinks. This may prove to be a good reason not to use flexible tubing in the field fitlers, although proper size and length of tubing increases the effectiveness. For removal of water the sinks were cleared and declogged so they could drain the water fast enough to allow the filter to run for much longer without the pool overflowing in filtration mode. To correct for the inconsistency in the coagulant flow 60 rpm was chosen as a random starting point to be used for the coagulant dosing, which would correspond to a flow of 168 mL/min. We would base our subsequent trials on the effectiveness of this inital starting point. The dilution of the stock coagulant needed for 168 mL/min was calculated to be 5.714 gm/L to keep the influent coagulant at 20 gm/L. To further investigate the maxed out influent of 1100 NTU, the clay mixture was run at half the flow (272 mL/min or 96 rpm) without any coagulant. This led to an influent turbidimeter that approached 500 NTU, so 96 rpm was used for subsequent runs. The clay mixture would also be more adequately stirred with the use of the stirrer. When the team received the stirrer in the mail, we set up a system out of support bars to hold the stirrer up in place above the mixture.

5 Results / Conclusions

1. Based on the experimental data and results for the filtration mode, it was found that the orifice equation which is used in the design code accounting for (1-ϵ where $\varepsilon$is the sand bed porosity) 60% slot coverage is a good estimate of the head loss through the slotted pipes. The experimentally observed head loss is actually less than the predicted head loss as depicted in Figure 5, which implies that during filtration mode, head loss through the slotted pipes is not an issue.

2. For the experimental runs using the small scale model-4 setup mimicking backwash, it was observed that the system did suffer higher head loss than theoritcally estimated by the design code. Since the code estimates

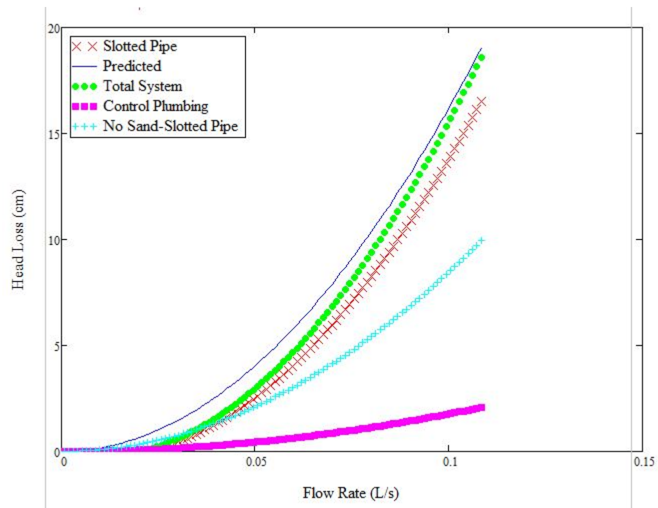

Figure 10: Experimental Results for Filtration Mode

the head loss using the orifice equation assuming no slot coverage , it was found that the equation underestimates the head loss as depicted in Figure 6. Experimentally, the correction factor for the area of the slots was found to be 2, which implies that double the slot area is required for the experimental values to converge with the predicted values used in the design code. In terms of slot coverage, a correction factor of 2 implies that 50% of the slots were covered during backwash initiation. Because double slotted pipes were used in the small scale model experiment but the backwash pipes in the filter are single slotted pipes, this means that an increase in slot area of 4 would be needed in the filter.

3. By going to 0.2 mm double sided slotted pipes for the backwash, there is an increase in the slot area by a factor of 2. The improvements in this area increase were seen experimentally. This led the team to delve further into investigating the option of using 0.3 mm slotted pipes for the backwash manifold since the team was still unable to run the backwash at design flow rate.

4. On running the filtration and backwash mode with 0.3 mm slotted pipes the team noticed a huge drop in the head loss. During filtration, the team observed overall head loss of 29 cm and inlet plumbing loss of 9 cm. The team was able to backwash it at the design flowrate of 0.8 L/s without changing any pipestubs in the inlet tank, with a head loss of 60cm. All the water was forced to go through only the backwash pipe. The team also used manometers to measure the head loss in the bottom 20 cm sand bed, which we measured around 15cm.

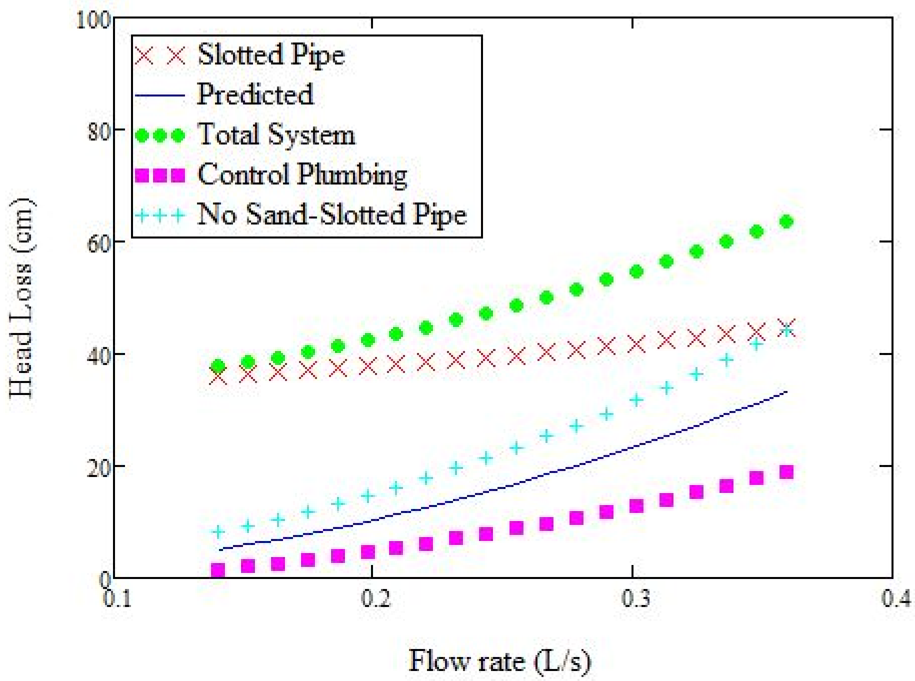

Figure 11: Head Loss during backwash mode with the sand bed fluidized.

6 Future Work

6.1 Continued Filter Performance Testing

For future work, performance testing of the filter will be key. The team will continue perfecting the experimental set up and figuring out an easy method of running the system and maintaining the runs for extended periods of time so that adequate data can be collected. After the completing the setup, the next step will be to record the pC* for multiple filter runs and to monitor the changes in head loss between clean, dirty, and clogged sand bed conditions. For the clogged conditions, the head loss required to initiate backwash needs to be determined.

6.2 Method to Enables the Operator to Know if the Sand is Fluidized

Another task for the future team is to figure out a method to ensure if the sand bed is fluidized during backwash. During backwash, with the help of the manometer we can measure the head loss across the bottom 20 cm sand bed. At clean sand bed and water conditions it was observed that the head loss across this 20 cm sand bed was about 15 cm, with a flow rate of 0.8 L/s. With a flow rate of 0.4 L/s, the measured headloss across the bottom 20 cm sandbed was about 12 cm, and when the flow rate was a bit above 0.8 L/s, the headloss was about 14 cm. We have yet to determine what exactly these findings are telling us, but if we can determine a way to use this information along with measurements for dirty or clogged sand beds, we may have a way of determining how fluidized the bed is given a certain measurement across the sand bed.

At our expected expansion rate of 1.3, we are looking at a superficial velocity of 15 mm/s. These calculations can be found in the referenced LyX document. Since we are hitting about 0.8 L/s, we can assume that the bed is roughly fluidized. Future work will have to be done to ensure that the entire cross-section is fluidized and not just specific regions.

6.3 Determing the Flow Distribution through the Slotted Pipes and Manifolds

In trying to determine whether the sand bed was fluidizing or not, the team had a lot of questions: What would be considered complete fluidization, or at least what amount of fluidization do we need for the filter, and were we able to achieve this in the filter? We used the small scale setup from Figure 4. The ideal fluidization is given as 30% sand bed expansion, and in previous experiments we had used previously determined upward velocity of 11 mm/s to get our 20 cm sand bed to fluidize, though we realized we never actually saw a 30% expansion. So, instead of using the theoretical flow rates, the team decided to mark at what point in the pipe the bed would need expand to in order to correspond to a 30% expansion, and then the highest flow rates we could manage with our system

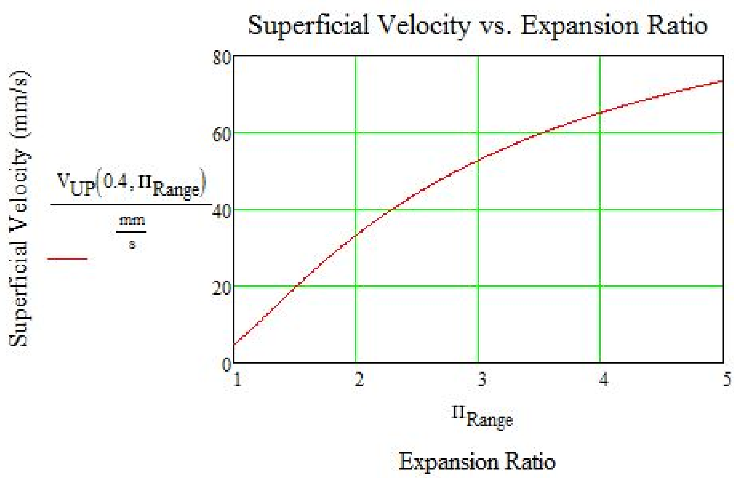

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Figure 12: Superficial Velocity vs. Expansion Ratio

were pushed through so we could determine what actual flow rate was needed for the expansion. At the highest flow rates much of the bed was expanded very high, past the 30% mark, however around the walls of the pipe, the bed was expanded very little or none.With lower flow rates, the circumference of the inner part of the sand bed that was fluidizing to 30% decreased. (A video of this is on the AguaClara Server: X:\RESEARCH\Low Flow Stacked Rapid Sand Filtration\Summer 2014\Pictures\fluidization.MOV)

This raised the question of uneven flow distribution through the sandbed-our system with only one slotted pipe in the 6 in pipe is probably under the influence of a lot more wall shear than what would be happening inside the actual filter, however there is still a good possibility that "dead zones" of pockets of sand that aren't getting fluidized are occuring within the manifolds in the filter much like we observed with our one pipe system. If this were the case, it could explain why backwash can be very inconsistent and takes a long time in the field. For the next team, trying to determine the flow distributions through the slotted pipes and manifolds could be extremely useful. First, comparing the flow through 0.2 mm slotted pipes and through 0.3 mm slotted pipes in our small scale system would help determine how much moving up to 0.3 mm slots affected the flow distribution. Then, by recreating a manifold and designing a small testing system that would allow for observation of how the water moves through the sand bed could be used to determine whether the entire bed is able to be fully fluidized with the manifold as it is designed now.

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