Low Flow Stacked Rapid Sand Filter

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Abstract

The Low Flow Stacked Rapid Sand Filter team seeks to design and build a 30 cm diameter filter that will accurately model the filters being constructed in India by AguaClara, LLC and to use the existing 10 cm diameter filter to quantify the effects of incorporating a backwash initiator and to construct an improved sand drain. The 10 cm team has constructed a constant head device, run the filter, and determined that the backwash initiator does not actually aid in the initiation of backwash, and is in practice a fluidization indicator. The 10 cm team has also constructed an alternative sand drain, but has not yet utilized it. The 30 cm diameter team has constructed a filter column, an inlet tank, and an exit tank. They have developed and implemented new methods to assemble these components, and they have documented their progress to facilitate the construction of new filters.

1 Introduction

While some developed countries have the ability to provide clean water to their citizens, developing countries may not have the same resources to provide clean water, especially in rapidly growing urban areas and in small towns. AguaClara, an engineering-based project team formed by Professor Monroe Weber-Shirk at Cornell University, works to combat this problem by creating efficient, cost-effective water treatment plants. With partner organization Agua Para el Pueblo, AguaClara has worked to design and build several water treatment plants in Honduras since its inception in 2005. Recently, AguaClara has begun work in India, where it hopes to apply its innovative water treatment technologies to new challenges, seeking to "improve drinking water quality through innovative research, knowledge transfer, open source engineering and design of sustainable, replicable water treatment systems."[1]

Low Flow Stacked Rapid Sand Filters (LFSRSFs), adaptations of stacked rapid sand filters optimized for flow rates less than 3 L/s, are an important technology currently being developed by the AguaClara project team.[2] In January 2013, Low Flow Stacked Rapid Sand Filters were tested in Honduras. AguaClara team members in Honduras faced substantive challenges in getting the filter to backwash, and stresses due to the filter's cross-country travel resulted in structural failure. This semester, the Low Flow Stacked Rapid Sand Filter team began construction of a new 30 cm diameter filter that will be easier to operate than previous models, with simplified hydraulic controls. Simultaneously, the team used an existing 10 cm diameter filter to quantify the effects of the backwash initiator in facilitating bed fluidization.

[1]https://confluence.cornell.edu/display/AGUACLARA/About+Us

[2]https://confluence.cornell.edu/display/AGUACLARA/Low+Flow+Stacked+Rapid+Sand+Filtration

2 Literature Review

2.1 A Physical Introduction to Fluid Mechanics by Alexander J. Smits

This text on Fluid Mechanics by Smits provides a basic understanding of the flow within the LFSRSF. This information is imperative to creating a design for the AguaClara LFSRSF which is based upon an understanding of the physics of the system rather than compensation with external devices such as pumps, etc. In particular, Smits' section on the energy equation for pipe flow is particularly useful, as he explains the major and minor losses and also energy losses due to valves and faucets. This knowledge aids in understanding flow through the LFSRSF, which is driven by a difference in piezometric head.

2.2 Fluid Mechanics 4th edition by Pijush Kundu and Ira Cohen

The text by Kundu and Cohen was used to supplement the understanding given by Smits. In particular, Kundu and Cohen provide an explanation of the orifice equation that will be potentially useful when alterations to the sand drain will be explored.

2.3 Novel Fluidic Control System for Stacked Rapid Sand Filters by Adelman, Weber-Shirk, Will, Cordero, Maher, and Lion

This paper presents the current hydraulic control system for the AguaClara Stacked Rapid Sand Filters which eliminates the need for mechanical controls. The water level in the filter is controlled by a siphon pipe. The siphon and a small diameter air valve eliminate the need for mechanical controls on the filter when switching between filtration and backwash. The backwash operational mode is begun by opening the air valve to initiate the backwash flow through the siphon. It is important to know this method of fluidic controls for several reasons. First, one of the goals of the 30 cm diameter team is to simplify the mechanical controls and reduce the number of valves needed to control the filter.

The current 10 cm diameter LFSRSF in the lab has 4 valves that control the inlet and 1 that controls the outlet. Second, the information on the fluidic control system is important in the understanding of the backwash system and the backwash initiator tests. Finally, the placement of the inlet tank to control flow in and out of the filter that is described will be replicated in the new 30 cm diameter filter.

2.4 LFSRSF – AguaClara Final Report – Summer 2013

In this report, the LFSRSF summer team (Alexander Balog, Rachael Brooks, Rishika Ghosh, William Pennock, and Samual Taube) outline the progress that they made with the Low Flow Stacked Rapid Sand Filter during the summer of 2013. The team was able to improve and develop several new features. The created a backwash initiator, which is a long rectangular shaped rod that displaces the sand in a clogged filter to give a preferential flow path to the backwash water. The rod is rotated from the top of the filter and displaces the sand radially. At the new AguaClara sites in India, the filters are opaque and the operators need to be able to determine if the sand bed has been fluidized or not. The team inserted a ball rod which, if it can move easily, indicates fluidized sand. Finally the team also investigated a method to drain the sand from the filter. Although they constructed a sand drain similar to the design being used in India, there is still room for improvement in this area.

3 Methods

3.1 10 cm Diameter Filter Subteam (Testing)

3.1.1 Manometer Construction

A clear pipe manometer (2) has been built in order to measure the head required for backwash (see18). The manometer is 2.44 meters high, and because of this, the team designed and built a structural support system to ensure that the moment created about the base of the manometer did not cause the filter to tip or the base to deflect (see 18). The moment of the weight of the manometer was calculated using the equation for a cantilever beam and a single load, the weight of the water in the manometer.

$$I = -Fd \tag{1}$$

where I is the moment of inertia, F is the force applied, and d is the distance from the load to the connection.

The maximum possible deflection of the PVC due to the manometer will be calculated using:

$$\delta_c = (\frac{Fa^3}{3EI})(1 + \frac{3b}{2a}) \tag{2}$$

Figure 1: 10 cm Diameter FilterThis 10 cm diameter filter will be used to test the backwash initiator and the sand drain.

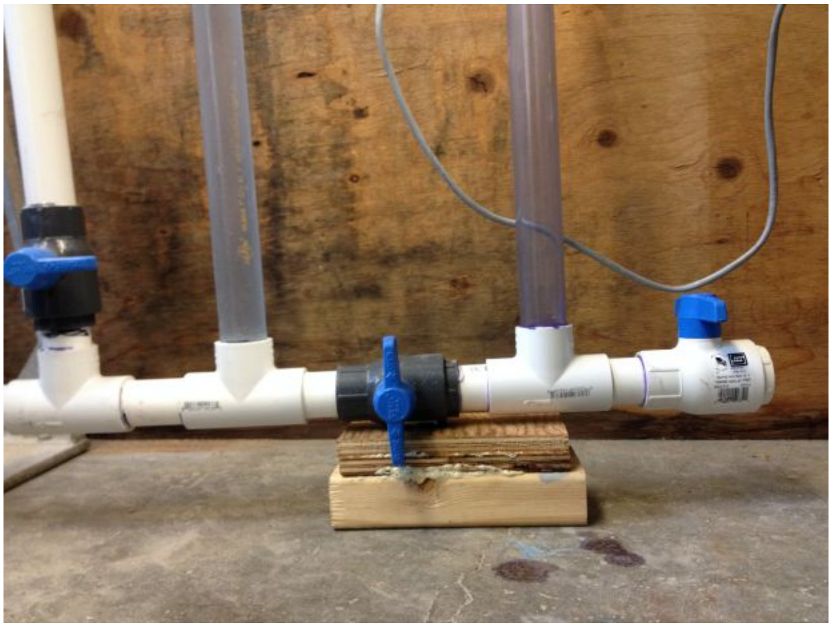

Figure 2: Manometer The clear pipe on the right is the manometer used to measure the head required for backwash. The valve in the center of the image is the valve to control flow to the manometer and the valve on the right is the manometer drain.

where E is the modulus of elasticity for PVC and a is the distance from the load to the free end of the cantilever.

After talking to Professor Weber-Shirk, it was decided that an additional valve was necessary. This valve will be attached to the influent pipe, in order to control the amount of influent water coming into the filter. This will help the team test the head loss created when backwash is occurring.

3.1.2 Backwash Initiator Testing

In order to begin testing the effectiveness of the backwash initiator, air bubbles were removed from the filter column and inlet tubing. Our intent was to fluidize a clean sandbed without the backwash initiator, measure the head required to achieve fluidization, and then repeat the process using the backwash initiator. The first attempt at fluidizing the sandbed was unsucessful. It was discovered that tubing connected to the inlet sump pump was faulty, so it was replaced inorder to maximize backwash flow.

Fluidization of the filter is achieved when volume of the sand has increased by 30%. Fluidization of a clean bed without the initiator was eventually achieved. However, the head required was larger than the head measurable with the manometer. The time required to fluidize the clean bed without the initiator was 446 seconds. Next the sand was fluidized using the backwash initiator. The time required to fluidize a clean bed with the initiator was 142 seconds. While using the backwash initiator, the manometer was unable to be used because of a lack of personel in the lab at the time.

Unfortunately, between test days, we discovered that there must be a leak somewhere in the top of the filter. During the two days between tests, a significant amount of air had entered the filter, which meant that the filter column was not air tight. The filter column was pressurized by adding water to the manometer and a bubble test was performed. It was discovered that the valve at the top of the filter column had failed and was leaking. A replacement valve was ordered and installed.

Using a clean sand bed, the head required to initiate backwash without the initiator was measured on the manometer to be 140.5 cm. According to 3, when ${}_{FiSand} = 0.4$ (the porosity of sand) and $\rho_{Sand} = 2650[kg/m^3]$ (the density of the sand), the head loss required for backwash is approximately equal to the height of the sand bed. The value measured using the manometer was slightly higher than the original height of the sand (130 cm) because the head loss also takes into account the minor losses from the plumbing of the filter.

$$HeadLoss_{FiBW} = H_{FiSand}(1 - {}_{FiSand})(\frac{\rho_{Sand}}{\rho_{Water}} - 1) \tag{3}$$

However, the 10 cm team encounter a dilemma when they attempted to measure the head loss required when the backwash initiator was in use. The way the head loss required for backwash was measured was to record the height of the manometer right before the bed fluidized and right after the bed achieved fluidization and then to take the average of the two heights. The backwash initiator was used to indicate whether or not the bed was fluidized. The team found they could not turn the initiator when the bed was not already fluidized, therefore, the dilemma was how to use the backwash initiator before the bed was fluidized. The summer 2013 filter team was consulted, and they said that they were able to turn the initiator before bed fluidization with some difficulty. The summer team believed they may have been able to turn the initiator because the filter was more securely fastened to its support system at the time. Despite efforts to secure the filter, the 10 cm team was still unable to turn the initiator with an unfluidized bed.

Given this setback, the 10 cm team decided to investigate another method to test whether or not backwash will be possible on the filters in India. A length of PVC was attached to the manometer drain at a height of 1.4 meters above the inlet of the sink. This will limit the ability of the laboratory pump to provide more flow than the 1.4 meters of head loss that is provided by the system in India. We decided to test with 1.4 meters of head loss because according to 3, the required head loss for backwash should be the height of the sand bed. The bed height is 1.2 meters, but there is also additional minor losses through the inflow PVC pipes, so the additional 0.2 meters was to account for that. With this design, we will be able to determine whether or not the filter will be able to achieve fluidization 3.

The filter continued to have problems with air leakage. A second pressurized bubble test was performed. It was discovered that the ball valve controlling the inlet to the filter had cracked along its threading, so the valve has been replaced..

With the filter now air tight, the 10 cm team clogged the filter with clay and a constant dose of coagulant, keeping the influent turbidity around 800 NTU to 1000 NTU. The coagulant was added to the filter at a concentration of 1 g/L and a flow rate of 23.94 g/hr. This was the dosage recommended by Casey and the flow rate that the Summer 2013 team had programmed into process controller. However, as the filter was run, it appeared that the coagulant supply was being depleted much more quickly than the process controller interface indicated. Although the coagulant dose may not have been accurate for current filter operation, since the goal was to clog the filter as quickly as possible the team decided that a higher coagulant dose would only aid in the clogging process.

The head loss pressure sensors were not working properly, so the team referred to the Summer 2013 LFSRSF team's records and discovered that it took the summer team 48 minutes to clog the filter with an influent turbidity of 500 NTU to 600 NTU, so the 10 cm team ran the filter for 45 minutes. Without the sensors in place, we were unable to observe the increase in head loss as the filter began to clog. Perhaps in the future, the inflow valve could be manipulated to show the head loss in the manometer, but during the preliminary testing, the manometer filled completely to the level of the 1.4 meters above the sink inlet.

Once 45 minutes had elapsed and a decrease in the effluent flow was observed, the filter was switched to backwash mode. Backwash mode entails closing all influent valves except the bottom one, closing the effluent valve, and opening the backwash valve. The valve leading the the 1.4 m constant head apparatus was also opened to limit the available head from the influent pump. After backwashing the filter at the constant head for 20 minutes, there was no fluidization of the bed, and it was impossible to turn the backwash initiator. The team concluded that the backwash initiator does not aid the filter in initiating backwash, it only acts as a backwash indicator. If the valve to the constant head apparatus were to be closed, fluidization of the bed could still be achieved.

3.1.3 Sand Drain Design

The current sand drain design requires that something (in this case - the palm of a human hand) stops flow through the sand drain, allowing the sand within the drain to settle in the length of pipe, which then allows the valve to close fully without being jammed by sand within the valve. The diameter of the sand drain in the lab is small enough that a human hand can create a perfect seal, however, if this method were to be implemented in Tamara, the plant operators would need to be trained to drain the sand and create the seal with their hand.

The 4" team has decided to increase the length of tubing used for the sand drain to longer than the height of the filter. This way, the flow of sand and water can be stopped by simply raising the end of the tubing higher than the filter. The sand drain is ready for use, but has not been tested because the filter was still in use and the team did not want to spend time draining the sand and

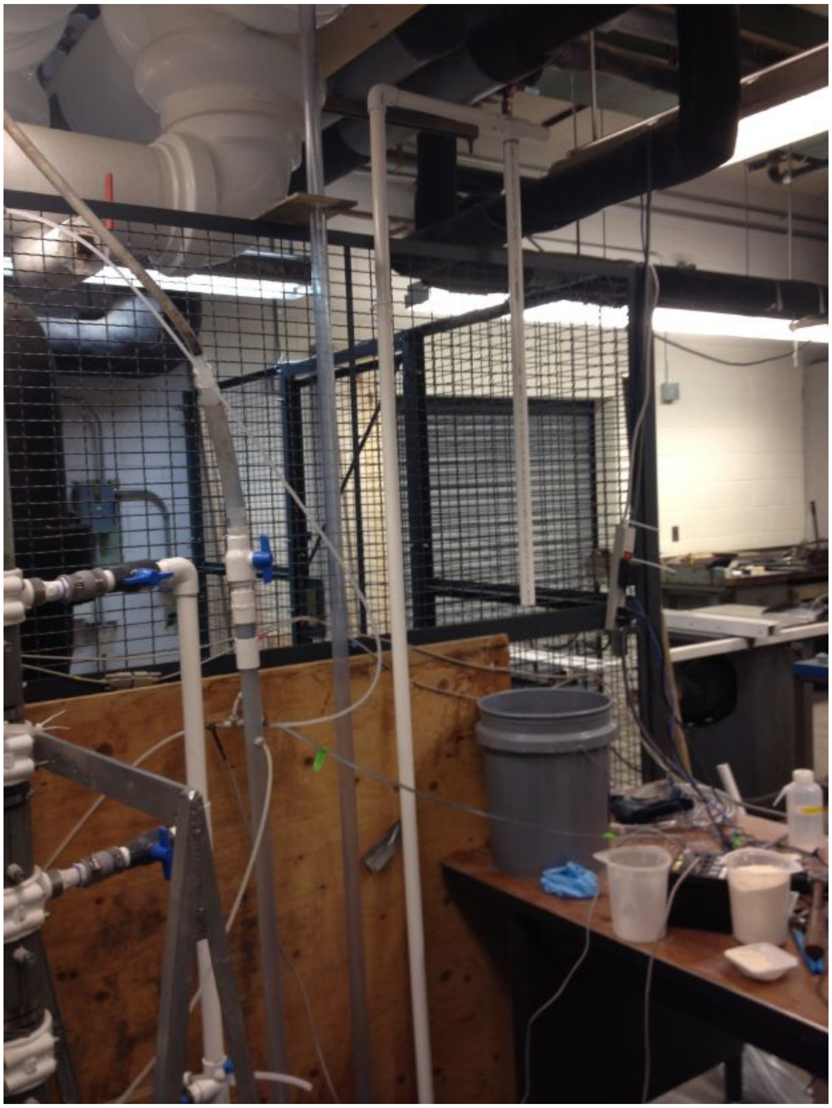

Figure 3: Constant Head The PVC pipe on the right creates 1.4 meters of head loss.

Figure 4: Bubble Test Result The valve at the top of the column after the bubble test showing a significant air leak.

then replacing it.

3.2 30 cm Diameter Filter Subteam

3.2.1 AutoCAD Drawings

The LFSRSF team contacted Maysoon Sharif to obtain AutoCAD plans of the filters being built in India. These AutoCAD drawings were taken apart piece by piece, with the dimensions of each part analyzed and added to a running list of part specifications. This allowed the team to identify specific parts based on their dimensions, and to begin creating a materials list of parts necessary for purchase that would allow the team to closely model filters currently being constructed in India.

3.2.2 Materials List

The dimensions of filter components extracted from the AutoCAD drawings were used to compile a comprehensive materials list. This materials list identified LFSRSF parts on the bases of quantity needed, AutoCAD drawing specifications versus purchase specifications, company of purchase, and total cost. The team obtained quotes by reaching out to a variety of manufacturing companies. Each necessary part was listed by a variety of manufacturers and specifications, to ensure that the team chose the best possible parts given their budget and desired filter specifications. Links to where the parts list materials could be purchased online were included with each entry. The materials list included a 30 cm diameter, 207.01 cm tall, schedule 40 PVC pipe to make up the filter's central column; slotted PVC piping to make up the slotted manifolds; PVC piping to connect the inlet and exit tanks to the filter column; inlet and outlet tanks; a ball valve to act as a simplified hydraulic control on the backwash effluent line; and adapter fittings to join filter pipes to the side of the filter and to the influent/effluent tanks.

3.2.3 Separable Filter Column

The fabricator in India identified a challenge in arranging the slotted manifolds and pipe fittings in the interior of the filter column, since the pipe is narrower than human shoulders in diameter and therefore hard to access. In response to this challenge, the fabricator split the filter column above the top inlet manifold to faciliate assembly of the plumbing inside the filter column. Building upon this technique, the 30 cm filter team devised a method to join the top and bottom filter pieces with a watertight seal made from rubber, stainless steel shimstock, and hose clamps. First, a cylindrical rubber gasket will be placed around the divide in the pipe halves. Next, a strip of stainless steel shim stock will be wrapped around the gasket, completely encircling the filter and with a few inches of overlap. The entire apparatus will be secured with two hose clamps, one above and one below the pipe divide. This method, seen in 5, provides a simple, cost-effective solution to the challenge of creating an accessible filter column interior. The same method of using rubber, stainless steel, and hose clamps to join PVC parts can be applied to add PVC caps to the top and bottom of the filter column. The team obtained a 61 cm x 61 cm x 1.3 cm PVC sheet, from which 32.4 cm diameter circles (the outer diameter of the main filter pipe) were cut; these circles eventually comprised the top and bottom of the filter.

3.2.4 Circular Plate Deflection

To determine whether the circular plates at the top and bottom of the filter column would be demonstrably deflected by the pressure inside of the filter, the team calculated the displacement 4 of a simply-supported 32.39 cm diameter circular plate under the uniformly distributed load of the pressure exerted on the filter by its contents.

$$Deflection = Pressure\frac{\left(R_{pipe}^{4}\right)(5 + Poissons)}{64D(1 + Poissons)} \tag{4}$$

where

$$D = thickness^{3}\frac{Youngs}{12(1 - Poissons^{2})} \tag{5}$$

The pipe radius R_{pipe} was 15.24 cm, Poisson's ratio for PVC was 0.38, and Young's modulus was 3.38 GPa. The thickness of the PVC plate analyzed was 1.27 cm. The team obtained this minimum thickness from the constraints of the width of the hose clamp band. The hose clamps are 1.27 cm wide, so this was also the minimum thickness of the PVC plate. Thus, the team found D=674 J.

Given the density of sand, 2650 kg/m^3; the porosity of sand, 0.4; the density of water, 1000 kg/m^3; the height of the sand bed, 1.3 m; and the radius of the pipe, 6 in; the team calculated the volume of sand in the bed, multiplying by (1 - porosity) to get the mass of sand in the filter 6.

$$M_{sand} = h_{sand}(\pi)(R_{pipe})^{2}(1 - porosity)(\rho_{sand}) = 139.2kg \tag{6}$$

To get the volume of water in the filter, the team subtracted the height of the sand bed from the height of the filter, 210 cm, and multiplied this quantity by the cross sectional area of the pipe. They then added the volume of water contained within the porous sand by multiplying the height of the sand bed times porosity and cross-sectional area of the filter pipe. By multiplying this volume by the density of water, the mass of water in the filter 7 was obtained.

$$M_{H_{2}0} = \left[(h_{filter} - h_{sand})\pi(R_{Pipe})^{2} + h_{sand}(porosity)\pi(R_{Pipe})^{2}\right]\rho_{H_{2}0} = 100.9kg \tag{7}$$

The pressure 8 exerted by the total mass was calculated to be:

$$Pressure = \left[\frac{(M_{H_{2}0} + M_{sand})\,9.8\frac{m}{s^{2}}}{\pi(R_{pipe})^{2}}\right] = 32.3kPa \tag{8}$$

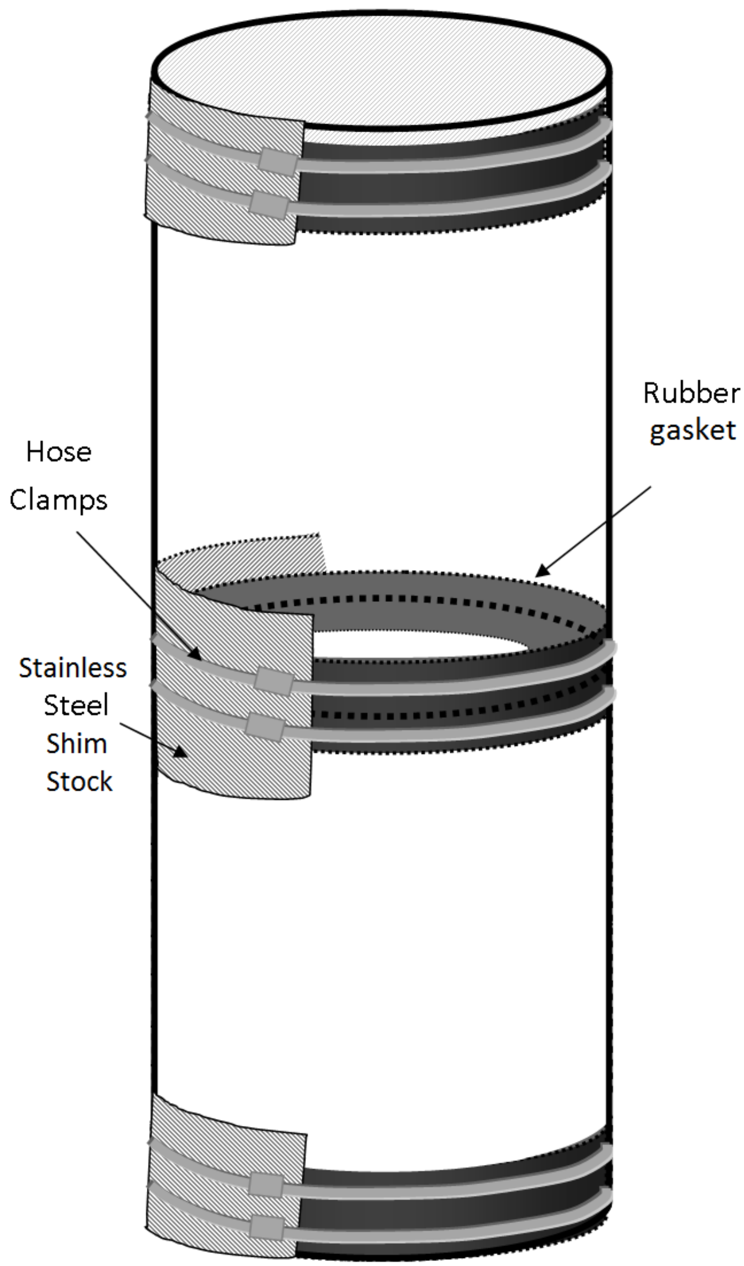

Figure 5: Filter Column in Two Parts. The team devised a method of creating a filter column that can be separated into two pieces so that slotted manifolds and other pipe fittings may be more easily added to the interior of the column. These two separable pipe pieces are joined with a combination of rubber, steel, and hose clamps. The top and bottom of the filter are held on with the same mechanism.

Substituting this pressure into equation 4, a maximum deflection of 1.572 mm was obtained. This degree of deflection was interpreted as relatively negligible as it is a small fraction of the plate's total thickness.

3.2.5 Inlet/Outlet Piping and the Backwash Trunk

Connecting the inlet and outlet tanks to the main filter column posed a formidable challenge, as these connections require seven pipes (four inlet pipes and three outlet pipes), which originate very close to one another in the bottom of the inlet and outlet tanks and therefore may obstruct each other's paths to join the side of the filter column. With rigid PVC, this was a difficult design problem, so the team decided to switch to flexible PVC piping instead. With flexible piping, inlet and outlet pipe connections could be placed in a vertical line on the side of the filter column. This design had the added benefit of minimizing head loss in the filter inlet and outlet pipes, since flexible tubing does not require 90ř elbow pipes. Rather, its larger radius of curvature is expected to reduce the minor losses of the bends in the inlet and outlet pipes.

The team then worked to calculate the necessary diameters for the inlet and outlet filter pipes. First, the team calculated the head loss through one layer of filter sand, as calculated by the Karmen Kozeny equation (9):

$$H_{Kozeny} = H_{FiSand}\,(36k)\,\frac{(1-\varepsilon_{FiSand})^2}{\varepsilon^3_{FiSand}}\,\frac{vV_{Fi}}{gD^2_{60}} = 7.06cm \qquad (9)$$

Here, k is 5, the porosity $\varepsilon$is 0.4, the height $H_{FiSand}$of one layer of filter sand is 20 cm, D is 0.7 mm, V_{fi} is 1.8 mm/s, and v is 10^{-6} m^2/s. This yields a total head loss through the sand layer of 7.06 cm.

The team then considered the head loss through the adapter fittings that would connect the flexible PVC pipe to the side of the filter and to the bottom of the entrance tank. This head loss is governed by equations 10, with the appropriate k factor determined by 11. The team first considered a 2.54 cm adapter, a size convenient in terms of both availability and price. Given the plant flow rate of 0.8 L/s, and for a pipe of diameter D_{out}=2.54 cm and an adapter of diameter D_{in}=1.905 cm, the team calculates head loss through one 2.54 cm barbed-to-male adapter :

$$H_{LAdapter} = k_e\left(\frac{Q^2}{2g(A^2_{out})}\right) = 7.7cm \qquad (10)$$

where:

$$k_e = \left(\frac{D_{out}}{D_{in}} - 1\right)^2 = 0.605 \qquad (11)$$

In designing the inlet piping for the filter, the team sought to maximize the flow ratio Π_Q (12), which illustrates the degree to which flow distribution between layers is uniform. Ideally, this ratio should approach 1, representing uniform distribution. They tested the results of 10 to see if 2.54 cm diameter inlet piping would yield a satisfactory Π_Q. Here, $\mathrm{H_{LAdapter}}$is given by 10. Since there are two adapters in the influent piping, both in the side of the filter and the bottom of the entrance tank, this value is multiplied by 2 in the Π_Q equation. $\mathrm{H_{Kozeny}}$is as found in 9.

$$\Pi_Q = \sqrt{\frac{\frac{2(H_{LAdapter})}{4} + H_{Kozeny}}{2\left(H_{LAdapter}\right) + H_{Kozeny}}} = 0.697 \tag{12}$$

Since it is impossible to maximize this ratio to 1, the team hoped to constrain Π_Q to about 0.80, representing a differential flow distribution of no less than 80%. Although the team calculated a Π_Q of 0.697, they nevertheless decided to proceed with the 2.54 cm design, deeming this flow ratio adequate. In the future, it may be possible to minimize the head loss $\mathrm{H_{LAdapter}}$ by replacing one of the adaptor fittings in the design with an alternative coupling. This is one of many efforts which may produce a more desirable Π_Q.

Next, the diameter of the backwash trunk was calculated 13. With a backwash manifold maximum velocity of 0.522 m/s, plant flow rate of 0.8 L/s, and matrix of available flex PVC diameters, the team found a minimum inner diameter of 1.74 in (4.42 cm) inner diameter for the backwash trunk:

$$Diameter = 2\sqrt{\frac{Q_{Fi}}{(\pi)\, V_{FiBwManMaxPR}}} = 1.74in \tag{13}$$

This formula calculates the necessary diameter of the pipe from a determined cross-sectional area. We use it to return a diameter for our backwash trunk given the area derived from filter flow rate and velocity.

As a result of these calculations, the team ordered flexible PVC of inner diameter 2.54 cm for the inlet and outlet piping, and flexible PVC of inner diameter 4.45 cm for the backwash trunk. The team could not obtain a 4.45 cm barbed fitting or coupling, so they instead decided to buy a 5.08 cm barbed fitting and 5.08 cm coupling. This was the best alternative to 4.45 cm fittings for various reasons. First, backwash manifold calculations were done according to a 5.08 cm trunk, so using a 5.08 cm coupling and barbed fitting is consistent with previous calculations. Additionally, the team was optimistic about their ability to connect a 4.45 cm diameter flexible pipe to a 5.08 cm fitting, as the PVC may be expanded under hot water and later hose clamped into place. Later experiments confirmed that a 4.45 cm diameter flexible pipe may be connected to a 5.08 cm barbed fitting after the flexible pipe has been submersed in hot water. This forms a strong, watertight seal.

3.2.6 Machining the Filter Column

With the inner diameters of the filter inlet and outlet pipes found to be 2.54 cm, the 30 cm filter team created a schematic 6 to facilitate the division of the filter column. This schematic was created based on the design constraints of the materials making up the filter, including the space between successive manifold trunks, the height of the shim stock, and the aforementioned nominal diameters of the inlet and outlet pipes. The team worked with Tim Bond in the Bovay Lab to machine the column with a bandsaw, as the filter's 32.4 cm outer diameter precluded its being machined in the Hollister lab.

The filter column was first cut down from 304.8 cm to 207 cm, the combined height of the two column halves as obtained from Maysoon Sharif's AutoCAD code. Next, the column was cut into 131.4 cm and 75.6 cm sections 7, as per the measurements of the schematic 6.

Next, the 30 cm filter team cut 32.4 cm diameter circles from 1.27 cm thick PVC sheet to form the top and bottom caps of the filter. These PVC circles were turned on a lathe to exactly match the outer diameter of the 30 cm filter column, so they could be attached to the filter column via the method detailed in 5.

Additionally, three pieces of stainless steel shim stock were sheared to a width of 3.8 cm to provide support while occupying minimal space at the top, bottom, and middle of the filter column. These pieces of shim stock were used to attach the caps at the ends of the filter as well as the two separated halves of the filter. The width of the shim stock is constrained by the width of the two hose clamp bands, each 1.3 cm, and includes a 1.3 cm allowance so that the bands may be placed slightly apart from one another.

3.2.7 Backwash Waste Pipe Design

The backwash waste pipe carries water from the top of the filter to waste during backwash. It is placed as high as possible on the side of the filter column to avoid the removal of fluidized sand during backwash. The target for the design of this pipe is to keep the head loss below 30 cm. The following equations give the minimum diameter of the backwash waste pipe given this constraint. 14 gives the head loss through the pipe as a function of average velocity V, which is given by 15.

$$V = \sqrt{\frac{2gH_e}{k}} = 1.534\frac{m}{s} \tag{14}$$

V is the average velocity through the pipe. k, which here has a value of 2.5, is determined by fluid contraction and expansion as water enters and exits the pipe, as well as by the 90 degree elbow in the pipe (See 8).

$$D = \sqrt{\frac{4Q}{\pi V}} = 2.578cm \tag{15}$$

Given the filter's flow rate of 0.8 L/s and maximum allowed head loss of 30 cm, we can calculate that the minimum allowed diameter for the backwash pipe is 2.578 cm (1.015 in).

If we decide to use flexible pipe for the backwash pipe, there is an additional head loss caused by the adapter. This is governed by 10 Considering an illustrative case of 2.54 cm diameter pipe, which is slightly smaller than the calculated minimum diameter, it can be found that the head loss through an adapter would

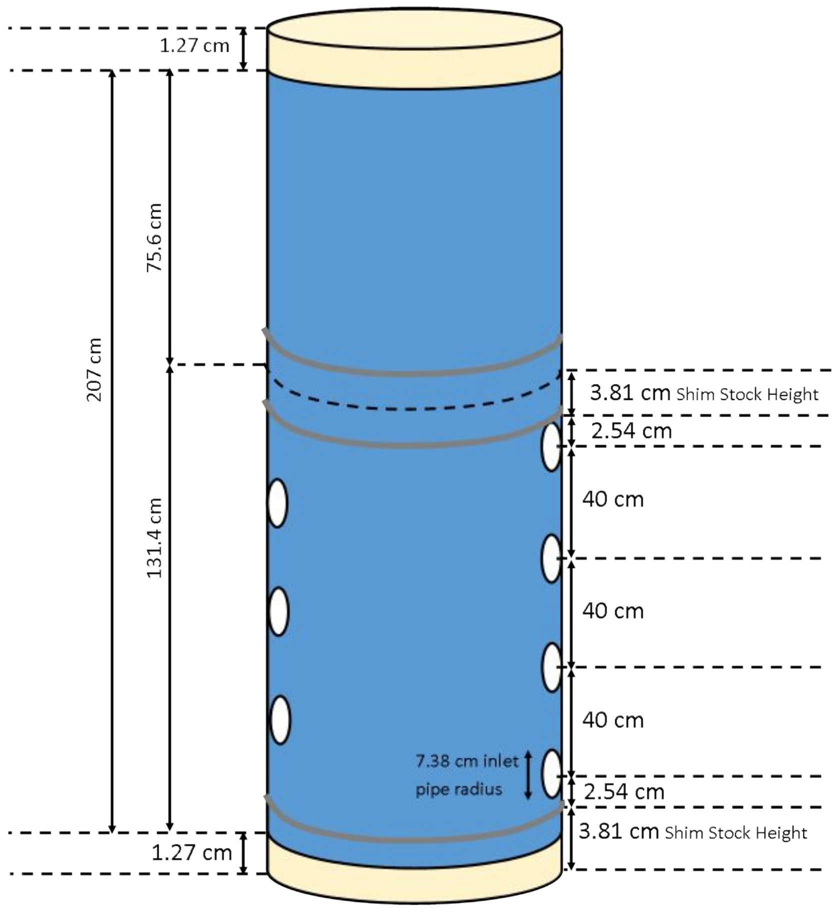

Figure 6: Schematic This schematic of the filter was used as a reference to machine the filter column. The blue cylinder represents the main filter column while the yellow plates represent the PVC caps at the top and bottom of the filter. The spacing of 20 cm from center to center of successive manifold trunks, as well as the diameter of the inlet/outlet piping, the height of the shim stock, and some small allowances helped us define where the pipe should be cut. The bottom half of the filter is 131.4 cm tall. This means it is tall enough to contain the entire 120 cm sand bed. The filter column's total height of 207 cm was obtained from Maysoon Sharif's AutoCAD code. Hole diameters were obtained from the dimensions of the barbed-to-male adapters that join inlet and exit pipes to the side of the filter. These adapter fittings will be screwed through the filter column's wall and into threaded couplings on the inside of the filter.

Figure 7: Filter Column Halves With the help of Tim Bond in the Bovay Lab, the 30 cm filter team was able to machine a 304.8 cm 30 cm diameter pipe into a 207 cm filter column. This column was then cut into two halves of 131.4 cm and 75.6 cm, respectively. The longer of the two columns will make up the bottom of the two filter halves. For reference, the team has placed a trial gasket, shim stock, two hose clamps, and a 1.29 cm PVC plate onto the smaller of the two columns. This reflects the method of attaching caps to the filter described in 5

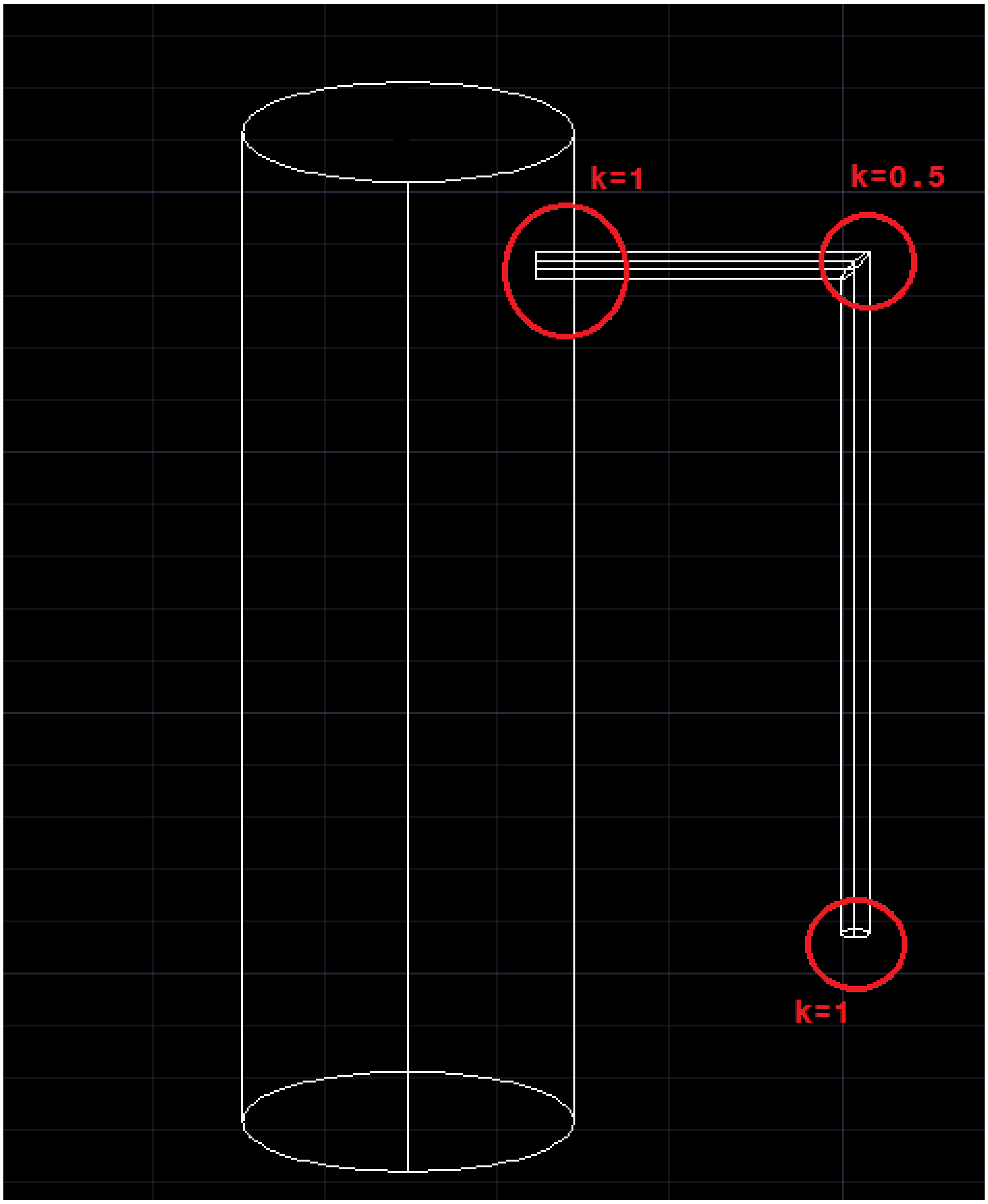

Figure 8: k factors throughout the backwash pipe The k factors are determined by the fluid contraction and expansion as water enters (k=1) and exits (k=1) the pipe, and by the 90 degree elbow in the pipe (k=0.5).

be 7.7 cm (see 10). The head loss caused by the adapter is very high when an adapter is introduced, so the team decided to instead use rigid PVC pipe and a female coupling to eliminate losses through the adapter. Furthermore, because the team was concerned that 2.54 cm was too close to the minimum diameter calculated in 15, they decided to use 3.81 cm diameter pipe for the backwash pipe, so that the head loss would not be so close to the maximum head loss that can be allowed. The team considered 3.18 cm diameter pipe as well, but this is not as standard of a pipe size (and therefore as readily available) as 3.81 cm pipe. Moreover, the 3.81 pipe sizes creates even smaller head losses because it has the greatest cross-sectional area of the three options. It is also worth noting that if the team later decides that a 3.18 cm diameter backwash pipe is preferable to 3.81 cm one, they can always use a reducer to convert to 3.18 cm diameter pipe, even after the 3.81 cm adapter hole has been drilled.

Applying these new design constraints to calculate head loss through the 3.81 cm pipe, we find:

$$H_e = \frac{kV^2}{2g} = 6.3cm \tag{16}$$

where:

$$V = \frac{4Q}{\pi D^2} = 0.702\frac{m}{s} \tag{17}$$

This yields a total head loss through the backwash pipe (16) of 6.3 cm.

Now considering the backwash head loss through the sand bed (18), we find that:

$$HL_{FiBwSS} = \frac{H_{FiSand}(\rho_{FiSand} - \rho_{H_2O})(1 - \varepsilon_{FiSand})}{\rho_{H_2O}} = 1.215m \tag{18}$$

The density of the sand, ρ_{sand}, is 2650 kg/m^3, the density of water, ρ_{H_2O}, is 1000 kg/m^3, and ε_{FiSand}, the porosity of the aquifer material, is 0.4. $\mathrm{H_{HiSand}}$is the height of the sandbed, 1.241 m. This is obtained from 19:

$$H_{FiSand} = (N_{FiLayer}-1)H_{FiLayer}+H_{FiBottomLayer}+outerradius(ND_{FiBwManBranch})+outerradius(ND_{FiMa} \tag{19}$$

As a preliminary calculation, it was estimated that 2.54 cm is the nominal diameter of the backwash trunk's manifold branches and 1.27 cm is the nominal diameter of the manifold branch for all other manifold trunks. $\mathrm{H_{FiBottomLayer}}$, the height from the backwash trunk to the first outlet (center to center), is 20 cm. $\mathrm{H_{FiLayer}}$, the height of a sand layer, is also 20 cm. $\mathrm{N_{FiLayer}}$ is 6, the number of filter layers. This gives a sandbed height of 1.227 m, and a backwash head loss through the sandbed of 1.215 m.

Finally, the team also estimated the major losses through the backwash pipe:

$$h_f = \frac{64}{Re}\frac{8}{g\pi^2}\frac{LQ^2}{D^5} = 3.98cm \tag{20}$$

Re, the Reynolds number, was assumed to be about 2100; Q, the flow rate, was 0.8 L/s; the total length L of the pipe was 1.98 m; and the diameter D of the backwash pipe was 3.81 cm. This calculation yields a head loss due to major losses of about 3.98 cm.

When 18 is combined with 14, 10, and 20, a total backwash head loss of approximately 1.32 m is obtained. This means that the bottom of the entrance tank must be at least this high. The team hopes that the results of these calculations may soon be corroborated experimentally.

3.2.8 Entrance and Exit Tanks

Seeking to simplify the filter's hydraulic controls, the team developed a design for the inlet and exit tanks that utilizes pipe stubs of varying height instead of valves 9. Five pipes connect to the bottom of the inlet tank 12: a 2.54 cm pipe carrying influent water, three 1 in pipes carrying water from the inlet tank to the top three manifold trunks of the filter, and a 4.45 cm backwash trunk carrying water from the inlet tank to the bottom manifold trunk. (These diameters were calculated in 13). These pipes are all made of flexible PVC tubing and will attach to the bottom of the tank with couplings, short pipe stubs, and hose clamps. The exit tank contains five 2.54 cm pipes: one carries effluent water out of the tank, one directs filtered water after backwash to waste, and three more carry water from the outlet pipes on the filters side into the exit tank. These pipes are also made out of flexible PVC tubing and are attached in the same method as the pipes of the entrance tank.

The inlet and exit tanks are made from 15.24 cm diameter PVC pipes and 1.27 cm thick PVC plates turned on a lathe to the outer diameter of these pipes. This diameter was constrained by the diameters of the 5 pipes attached to the bottom of the inlet tank, as described above. It was necessary that all five holes drilled to fit the couplings would fit comfortably within a circle with the inner diameter of the PVC pipe comprising the tank walls. The team investigated possible pipe configurations and tank diameters by creating scale drawings with a compass. It was determined that a 15.24 cm nominal diameter pipe would comfortably yet closely fit all five necessary pipes, so it was chosen as the diameter for the tank.

The 0.77 cm thick PVC plates are attached to the 15.24 cm diameter pipes to form watertight tanks according to the method described in 5. 15.24 cm gaskets were placed over the joins between tank and cap, wrapped with 3.81 cm wide stainless steel shim stock, and secured with hose clamps. This construction method was motivated by the height of the inlet and exit tanks, which precluded the use of a preexisting PVC or plastic container. The inlet tank, the taller of the two tanks, must include a 15 cm minimum pipe stub height for the inlet-to-filter pipe placed lowest on the filter, 5 cm more for each of two other pipe stubs, a further 40 cm for the head loss through the filter, and finally 5 cm of freeboard.

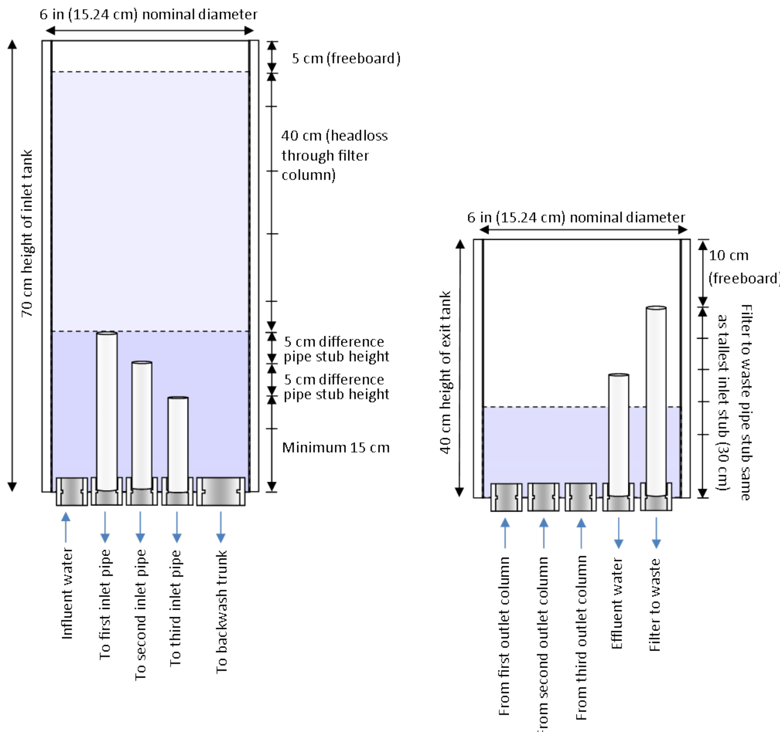

Figure 9: Inlet and Exit Tanks This figure depicts the inlet and exit tanks of the 30 cm diameter filter. These tanks are comprised of 15.24 cm diameter PVC pipes, which are capped with 1.27 cm PVC plates according to the method described in 7 Couplings are inserted through the circular plate to allow for the insertion of pipe stubs on the interior of the tanks and to allow for the attachment of flexible PVC tubing on the underside. The constraints on pipe stub and tank heights are discussed in Section 3.2.8.

Figure 10: Coupling Test A hole was drilled in a 1.27 cm thick PVC sheet using a 12.7 cm hole saw. A coupling was then inserted through the hole, and PVC glue was applied around the edges to create a watertight seal.

This represents a total tank height of 70 cm, a height too tall to allow for the use of an existing tank or bucket. (The exit tank is constrained to a height of 40 cm, as seen in 9). By using a PVC pipe cut to this height, the LFSRSF team was able to precisely control the dimensions of the inlet and exit tanks.

Pipe stubs of 15 cm, 20 cm, and 25 cm will be inserted into the three 2.54 cm inlet-to-filter pipe couplings from the interior of the tank, as shown in 9. These heights will control flow through the plant, so that falling water levels stop flow through each inlet pipe in succession until only the backwash pipe remains in use. The exit tank will feature two pipe stubs: one inserted into the filter-to-waste coupling, the other into the effluent water coupling. The top of the filter-to-waste pipe stub will be level with the tallest (25 cm tall) pipe stub in the inlet tank. The effluent water pipe stub will be shorter than this constraining height. This will ensure that water will only be directed to waste when the pipe stubs are switched.

3.2.9 Machining the Entrance and Exit Tanks

Two gaskets of 15.24 cm diameter were obtained by cutting a Fernco gasket in half with a bandsaw. Shim stock of approximately 3.8 cm by 61 cm was sheared to size. Adjustable length hose clamps were obtained to cut to size.

1.27 cm thick PVC plates were marked with the inner and outer diameters of the 15.24 cm pipe. The outer diameters were cut with a bandsaw and then turned on a lathe to precise size. Holes representing the couplings that will be inserted through the plate were positioned using a ruler and a compass in the space marked by the pipe's inner diameter, as shown in 11. These holes were cut with 4.13 cm and 7.38 cm hole saws. The former dimension allows for the insertion of 2.54 cm couplings, while the latter fits a 5.08 cm coupling (for

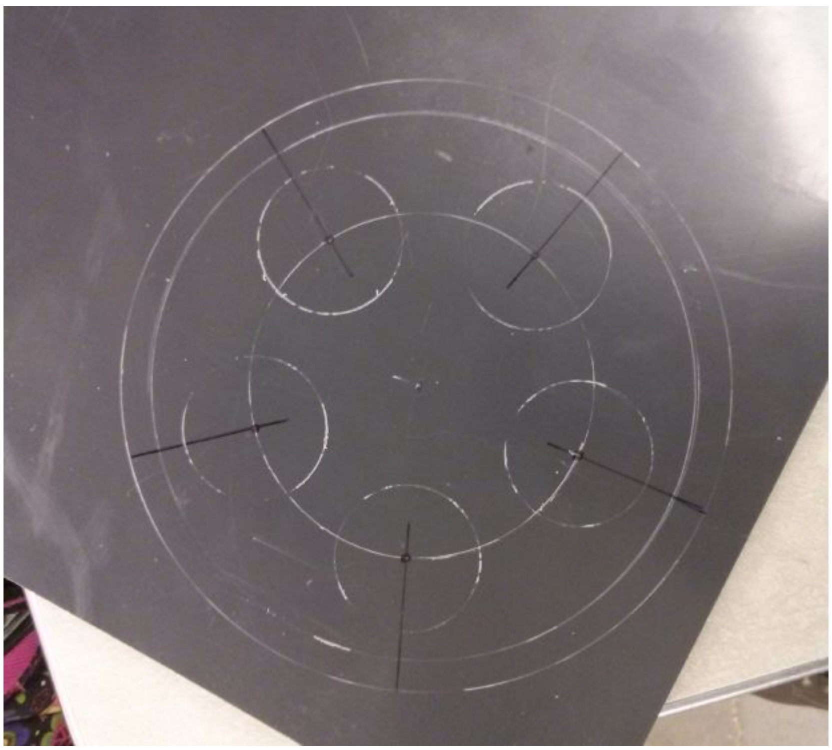

Figure 11: Machining the Exit Tank Cap The outer white line represents the outer diameter of the tank. The inner concentric ring represents the inner diameter of the pipe. The locations of the holes for the couplings have been marked in Sharpie. They will ultimately be drilled with a hole saw.

Figure 12: Exit and Entrance Tanks The 40-cm-tall exit tank, shown left, features five 1.27 cm barbed-to-male adapter fittings that screw into 1.27 cm couplings. These couplings have been glued (with PVC glue) into the tank's bottom plate, through holes cut with a hole saw. This plate is attached with a gasket, stainless steel shim stock, and hose clamps. The exit tank, shown right, features four 1.27 fittings identical to those of the exit tank. It also features a larger hole, into which a 5.08 cm coupling and 5.08 cm barbed-to-male adapter fitting have since been attached.

the backwash trunk pipe). Once these holes were cut, unthreaded couplings, primed with PVC primer, were inserted into the holes and attached with PVC glue. The team tested this design in 10 and, satisfied with its results, quickly began its implementation. Though the holes drilled in the PVC caps with the hole saws were somewhat sloppier than the initial test hole, and the exit tank sprang some small leaks around the couplings, the team was able to improve these seals and make them watertight by injecting PVC glue with a syringe into the space surrounding the couplings.

3.2.10 Attaching the Entrance and Exit Tanks

The inlet and exit tanks are attached to the side of the filter with hose clamps and two rigid spacers (see 13) cut from PVC sheet. This allows the tanks to be supported at varying heights, and will allow them to be removable from the side of the filter if necessary. The spacers set the tanks slightly off from the filter's main column and slightly apart from one another in order to allow for the extra diameter of the gaskets used to cap both column and tanks. The filter column

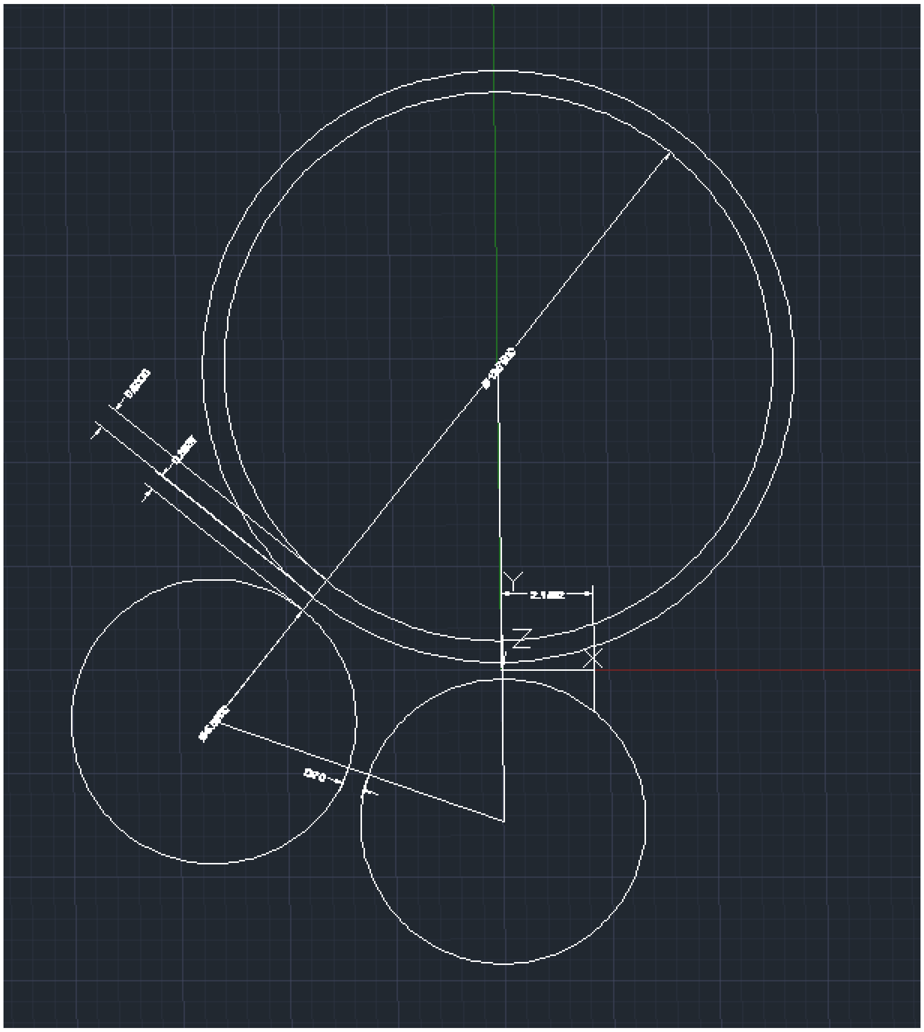

Figure 13: Spacer Design The spacer design was constrained by the outer diameters of the inlet tank, exit tank, and filter column, as well as by the extra width added by the gaskets holding caps on each of these three pipes. This figure depicts a to-scale rendering of the spacer design completed in AutoCAD. The two small circles of equal size represent the outer diameter of the inlet and exit tanks. The larger concentric circles represent the filter column and the gasket around it. The gasket width was taken as 1.27 cm, and a further 1 cm of space was inserted between the edge of the gasket and the edge of each tank to provide easy clearance between the filter and tanks, as well as to add some extra width to the spacer. When the PVC sheet is cut into narrow strips, it becomes weaker, so creating a piece of substantial width was important to preserve its structural integrity. The inlet and exit tanks were placed 1.27 cm away from each other, which allowed for the width of the exit tank's gasket.

Figure 14: Spacer A spacer was machined from a 1.27 cm thick piece of PVC sheet. It was cut with a bandsaw according to the specifications of 13 and then milled precisely to size. The spacer holds the entrance and exit tanks onto the side of the 30 cm filter column.

features two spacers, separated vertically, to ensure that the tanks held steady in place.

An AutoCAD design was created (13) to make this pattern easily replicable for future filter construction. The design was transferred onto the PVC sheeting with compasses and straight edges, and the spacer was cut out with a bandsaw (14). After it was cut, the spacer was milled down to size, using 30 cm and 16.4 cm pipes as references. This helped to create a more accurate cut than was possible with only a bandsaw. A skilled machinist could complete the spacer using only the bandsaw if necessary, however. The pattern was retraced to cut the second of the two spacers. In the future, though, the team recommends that both spacers be cut at the same time to more easily ensure they are identical.

Once cut, the spacers were attached to the side of the filter using PVC glue. They were placed on the same side of the filter as the inlet and outlet adapters and were postitioned with a level. They were then hose-clamped into place and left to dry. The spacers were placed about 22 cm apart vertically, and lined up exactly horizontally. They were placed, roughly, in the upper two-thirds of the top half of the filter column. Their precise vertical position was not deemed important, provided that it allowed for the tanks to be held significantly higher than 1.32 m above the ground, the head loss calculated during backwash. The team was satisfied that this was the case.

Figure 15: Attaching Spacers with Level The two spacers were attached to the side of the filter column using PVC primer and PVC glue. They were placed so as to be parallel with the floor; this was ensured with the use of a level. Once glued, they were secured to dry with a hose clamp.

Once the two spacers were glued to the side of the filter, the entrance and exit tanks were lifted into position and secured with hose clamps, as seen in 16.

3.2.11 Backwash Pipe Construction

With the entrance and exit tanks completed, the 30 cm team began construction of the 3.81 cm backwash pipe. A hole was drilled into the side of the filter column, into which a 3.81 cm coupling was inserted and glued into place (see 17). A small 3.81 cm diameter pipe stub will later be used to attach this coupling to a downward-pointing 90 degree elbow pipe, also of 3.81 cm diameter. This elbow will be connected to a ball valve via another small pipe stub, which will in turn be connected via pipe stub to a 3.81 cm diameter union. All of these connections will be glued into place with PVC glue. Finally, a long section of 3.81 cm diameter pipe will be glued into the union and allowed to reach almost the floor. The exact specifications of this pipe must be determined by future teams. The 30 cm team has already obtained all of the necessary materials for the construction of the backwash pipe, and the completion of its construction should be very straightforward.

4 Conclusions

This semester, the 30 cm filter subteam was able to successfully construct a watertight filter column, made separable so as to facilitate filter construction and the later insertion of slotted manifolds, as well as watertight filter entrance and exit tanks. The technique of joining two PVC columns with a gasket, stainless steel shim stock, and hose clamps was refined and executed to great success in the construction of the main filter column, entrance tank, and exit tank. The team designed and implemented spacers to attach these entrance and exit tanks to the filter column, and they were able to sucessfully mount the tanks on the filter's side. The team has also carefully studied the constraints governing the design of filter components and has calculated head loss through various parts of the filter. 30 cm subteams in coming semesters will be well-positioned to move into further stages of construction and testing as a result of the accomplishments of this semester's subteam. The subteam was quite effective in accomplishing its goals, even though it was not able to address all of the challenges on its task list. For example, the design of the slotted manifolds of the filter still poses a significant challenge. However, the team believes this challenge might be easily surmountable once filter testing begins and various design constraints can be tested experimentally.

The 10 cm testing subteam has determined that the time required for backwash while using the initiator was much shorter. Although this seemed to be an indication that there was less head required for backwash with the initiator, once the filter had been clogged and backwash was attempted maintaining a constant available head of 1.4 m, the testing subteam was unable to turn the backwash initiator and unable to achieve bed fluidization. Therefore, it was concluded

Figure 16: Tanks Supported on Filter Side With the spacers attached, the entrance and exit tanks were placed against the spacers and secured with hose clamps. From here, the flexible pipes connecting the tanks and the inlet and outlet barbed-to-male fittings may be attached.

Figure 17: Backwash Pipe Construction This 3.81 cm coupling, which will ultimately fit the backwash pipe, was glued into the side of the filter column, close to the top cap. This hole was drilled with a 5.72 cm hole saw whose blades had been sanded slightly inward. The coupling was attached with PVC glue.

that the backwash initiator does not aid with the initiation of backwash. It has been shown to reduce the time required for backwash once the bed has already been fluidized, it has also helped break up plugs, and it is a good indicator of whether or not the bed has been fluidized. An alternative sand drain has also been assembled and is ready to use once the filter needs to be drained.

5 Future Work

Future 30 cm filter teams must finish the assembly of the filter and work to get it up and running. Flexible tubing must be cut to appropriate lengths and attached to the barbed-to-male adapter fittings so the entrance and exit tanks may be connected with the side of the filter column. The backwash pipe must be assembled, as detailed in Section 3.2.11. All of the necessary materials for the backwash pipe have been obtained, so a future team will simply have to cut the 3.81 cm PVC pipe to size and glue the pipe fittings together as appropriate. Future teams should also investigate different specifications of slotted manifold piping. The current 30 cm team advises that future teams test manifold piping experimentally rather than try to describe headloss and design constraints for the manifolds with complicated equations; since the filter has been built, it should be very simple to try out different manifolds and see if they are effective. Thought will also be required to properly design the pipe stubs that will be used in the entrance and exit tanks. These pipe stubs must be of very specific heights, many of which may be determined experimentally. It is also worth considering that the pipe stubs will create a significant k factor contribution when they are inserted into the tanks, caused by the constriction of the flow of water as it enters the pipe stubs from above. The possibility of putting caps into which small orifices have been drilled on these pipe stubs may help to minimize the ensuing headloss.

The 10 cm team needs to work on a method on determining the headloss required to backwash the filter by creating a way to vary the constant head available to backwash. Although they have determined that the backwash initiator is insufficient for initiating backwash at a constant head of 1.4 meters, they need to determine how the filter will be backwashed, either by two phases or by increasing the available head.

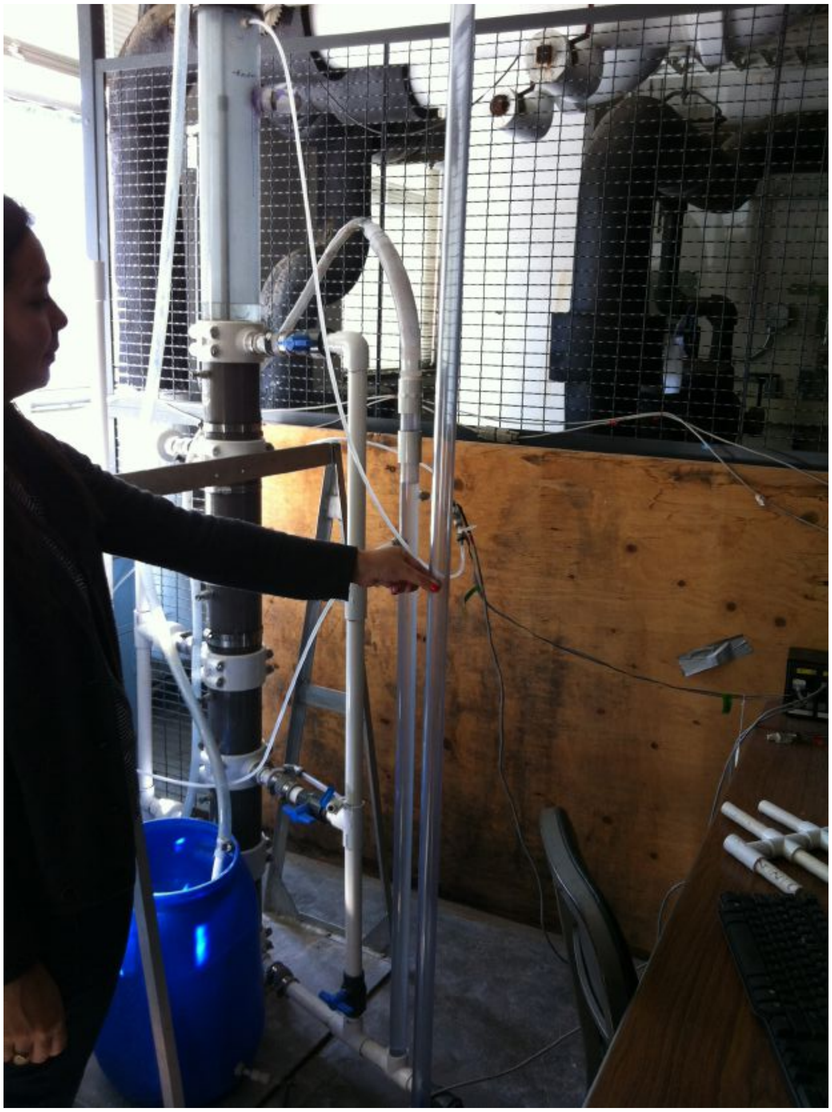

Figure 18: ManometerThis is the PVC pipe that was used to construct the manometer.

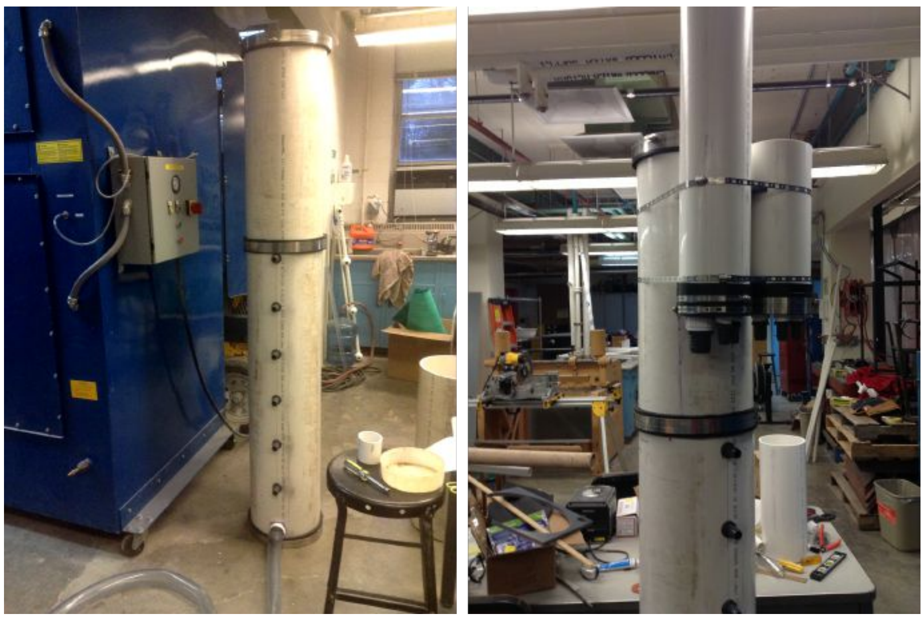

Figure 19: Assembled Filter The filter in the process of being assembled. The separable pieces of the filter have been joined with gaskets, hose clamps, and shim stock, and couplings and adapters have been screwed together through the filter column wall. The entrance and exit tanks have been attached to the front of the filter column with hose clamps and PVC spacers (right), and a coupling has been glued into the side of the filter for the backwash pipe. The backwash waste pipe must be constructed, slotted manifolds installed, flexible PVC piping cut and attached to the barbed adapters, and pipe stubs added to the inlet and exit tanks by future LFSRSF subteams.