Low Flow Stacked Rapid Sand Filtration - Final Report

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May 11, 2013

Abstract

In January 2013, the Low Flow Stacked Rapid Sand Filter (LFSRSF) was tested in Honduras. Although the filter worked, it quickly failed due to structural weaknesses. The primary tasks this year include improving the durability of the filter and increasing the ease of operation. New manifold and sand drain designs are in the process of being implemented. Additionally, the stacked rapid sand filter (SRSF) went to Washington, D.C., in April for the EPA P3 competition. A written proposal for the EPA P3 grant was composed and submitted. To demonstrate the design and effectivess of the LFSRSF, a fully operational unit was designed. The prototype underwent hydraulic and performance testing and operated well at the competition.

Introduction

One of the essential components of human life is accessibility to clean drinking water; however, much of the world suffers a deficiency of this vital resource. In the mean time, the remainder of the countries are able to utilize modern technology to treat raw water and enjoy the benefits of pathogen free and low turbidity drinking water. For example, the United States is able to utilize its wealth and availability of electrical power to treat raw water; yet, not all countries are fortunate enough to have these resources. Therefore, the AguaClara project's aim is to provide an economical and electricity-free drinking water solution that can be implemented all over the world, especially in regions with economic hardships and power shortages. This goal was accomplished through the development of the AguaClara treatment facility, which is currently being utilized in several locations in Honduras. To further optimize this treatment facility, the conventional filtration process was investigated to determine the aspects of the process which could be improved. The goal of this team's specific research project is to modify the current design of the LFSRSF so that it may be implemented by Agua Para el Pueblo and other non-governmental organizations (NGO's) and used in any subsequent water treatment facilities. Previously, a stacked rapid sand filtration system was designed to remove the particles remaining after sedimentation in an efficient manner prior to chlorination and distribution. However, this method is unable to treat flows less than 6 liters per second. Smaller communities, who have water treatment plants with less flow, would be unable to use this system. Thus, a design and prototype low flow filter was created within the last year. However, the design is not fully complete, and testing and modification of the system is necessary before it can be implemented in a plant.

1 Literature Review

1.1 EPA P3 Phase 2 Project Report for the Foam Filter (2012)

The Phase 2 report for the Foam Filter was used as a reference in the process of writing the Phase 2 report for the SRSF. A large component of the report was focused on the benefits of the filter to P3's major topics of people, prosperity, and the planet, and since much of this information was relevant to AguaClara in general, it was useful as a foundation for the new proposal.

The Foam Filter proposal discussed the issue of access to clean water throughout the world, citing data from various reports about the scope of this need and the degree to which it remains unfulfilled. This report also commented on the success, or lack thereof, of the UN's Millennium Development Goals and noted the difference between "safe" and simply "improved" water sources. The water treated by an AguaClara plant, for example, can be considered safe water, because the treated water is expected to meet a standard Nephelometric Turbidity Unit (NTU) and removal of bacteria. However, according to some standards, "improved" access to water can include the piping of untreated water to households.

The Foam Filter report also compared the technology to other more traditional methods of water filtration. Because the foam filter was initially considered for either point of use or emergency water treatment, part of this comparison included its viability as an emergency response system, and noted the issues with current methods in terms of response time and failure rates. Citing aspects of the overall AguaClara design philosophy, the report discussed how the technology was designed specifically to be sustainable within a community and avoid failure, particularly that which would be difficult to repair.

The practices of using cheap, locally available materials, and designing purely hydraulic systems were cited as components of the technology that made it beneficial to the people it would serve, as it is designed to be a financially viable system that is intended to improve the quality of life of a community. Reduction in the needs for electricity and plastic water bottles were both given as environmentally beneficial consequences of the technology.

1.2 Documentation on the Stack Rapid Sand Filter's Report for EPA P3 Phase 1

Last year, the SRSF team won Phase 1 of the competition based on a report describing the project's relevance and benefit to communities. The report also described the necessary future work and expected expenses. The document discussed the innovation, fundamental theory, and flow paths associated with the stacked rapid sand filter. Additionally, it described the three aspects of sustainability; people, prosperity, and planet; and their relevance to the filtration method. For social sustainability, the research plan discussed Agua Para el Pueblo (APP) as well as the use of an elected water board in each community to oversee the management of the AguaClara plant. For economic sustainability, the plan discussed the monthly operational costs per household and the manner in which chemicals and materials for the plant will be acquired. For environmental sustainability, the report discussed the reduction in backwash water which is required for a SRSF, as opposed to a conventional rapid sand filter, and the filter's use of gravitational potential energy verses solar or electrical power. Laboratory experiments were completed for the SRSF and yielded excellent reductions in effluent turbidity and significant reductions in backwash time required for contaminant and colloid removal (~ 7 minutes).

1.3 Previous AguaClara Filter Teams' Reports

In previous years, research mostly focused on features of the SRSF such as the flow distribution between the six sand layers, the difference in efficiency of turbidity removal by the up-flow and down-flow sand layers, and the optimum time required for backwash to achieve ideal sand cleansing. This data is relevant to the low flow version of the filter as well; therefore included in this report. From various experiments run in the lab, it was determined that the flow through each sand bed was uniform (1) and the upflow and downflow turbidity removal was the same. Various switching methods between filtration and backwash mode were also studied, and it was decided that a siphon control system would be the ideal choice wherein a single valve would be needed to initiate the switch.

2 Methods

2.1 Small Scale Filter (for EPA P3 Competition)

A small scale prototype was built for the EPA Phase 2 competition. The design techniques used were similar to those for the full scale filter including the calculation of the required dimensions of the tubes, manifolds, and filter column. The dimensions were calculated using the backwash constraint for fluidization of the sand grains as well as the head loss during both filtration and backwash. The estimated flow rate required is 0.022 L/s. The filter body was constructed out of clear polycarbonate tubing to ensure maximum visibility.

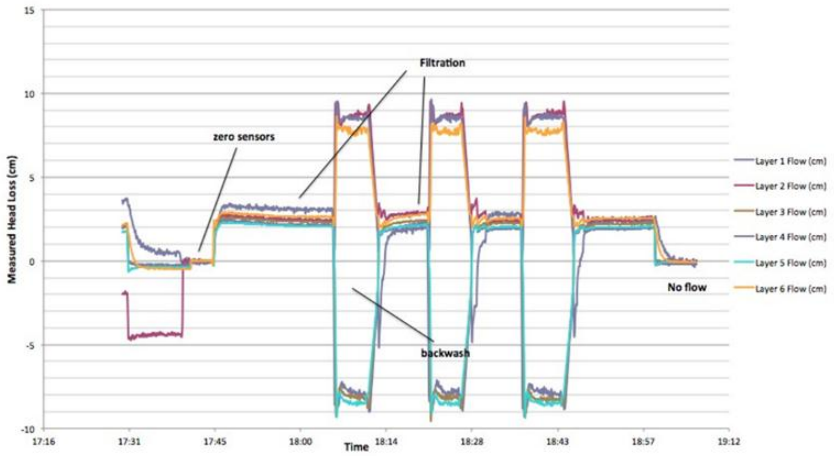

Figure 1: Flow Distribution

To emulate the manifold construction, a circular wire mesh design was incorporated because the current manifold design for the low flow SRSF could not be scaled down to such a size. A casing for the mesh was created from 3/8" polycarbonate tubes which are drilled with multiple holes to allow the water to enter the main filter column. The main column itself was manufactured from polycarbonate tubing with an inner diameter of 2 inches and a height of 6 ft. The manifolds are drilled through the main column with a distance of 20 cm separating each inlet and outlet. The bottom of the filter is closed off by a polycarbonate plate while the top has a detachable grooved cap that is made air tight with an o-ring. 3/8 inch quick connects are used to connect the manifolds to the external piping system. The general layout of the setup is similar to the original design; however additional ball valves were added to each inlet and outlet to prevent the flow from taking shortcuts through the manifolds during backwash, as check valves are not applicable at such low flow rates.

The frame to support the whole set up was created out of 80/20 steel bars with an inverted T cross section. The frame has a height of 6 ft, length of 4 ft and a width of 2 ft. The frame was assembled in such a way as to enable easy deconstruction and reconstruction, to facilitate easy transport of the set up. Additionally, it was designed keeping in mind that the set up will rest on a standard 2 1/2 ft table. It has bench clamps to hold it in place and clamps to attach the filter column to the front of the frame. To balance the weight of the filter, the bucket containing the water was suspended from the back of the frame. See Figure 2 for an illustration of the setup.

Design of the small scale filter has illuminated issues with scaling the existing LFSRSF design; consequently modifications in the small scale design have occurred. In an attempt to scale down the full scale filter, the velocity through the sand bed layers during the filtration cycle was kept constant, while decreasing the flow rate and cross sectional area. Thus, the flow rate for the small scale filter was computed to be 0.04 L/s. This is greater than the original 0.022 L/s due to changes in the original design. The rate of 0.04 L/s was deemed necessary because it provided sufficient backwash velocity to completely fluidize all the sand layers. The constant head tank, a suspended bucket, was used for the small scale filter to provide the driving head required for operation. To determine the height of water necessary to provide the 0.04 L/s flow the following equation was used to solve for h: $Q = 0.62A\sqrt{2gh}$. In addition, a factor of safety of 1.5 was applied to the required flow rate to ensure sufficient head; thus the design rate was 0.06 L/s. Using the specified flow rate and diameter of 0.75 inches as the diameter of the orifice at the bottom of the constant head tank, a head of 25 cm above the orifice was computed to be needed. In addition to computing the flow rates needed for the design to be hydraulically functional, the head loss was also computed for both filtration and backwash cycles. To calculate these two head losses the major and minor head losses were computed for each pipe segment over its length, as well as any expansions or contactions in the flow due to pipe diameter variability.The head losses during filtration and backwash were computed to be 0.65 ft and 4 ft, respectively. The equations used to compute the major and minor head losses are as follows:$h_{major} = f\frac{8}{g\pi^2}\frac{LQ^2}{D^5}$; $h_{minor} = K_e\frac{V^2}{2g}$. The equation used to compute the major head losses is for the case when the flow is turbulent. In order to have conservative estimates of the head loss, the flow for both filtration and backwash was assumed to be turbulent.

The maximum flow rate, 0.04 L/s, through the system was too great during the filtration cycle and caused the sand located directly next to the inlets to fluidize. Therefore, a valve at the entrance of the filter was added to allow the flow to be reduced during filtration and increased during backwash as needed. Due to limited resources at the competition and the overall goal for preservation, water was recycled through the system, which meant that very turbid water continuously travelled through the mesh in the manifolds that were used for the small scale filter (as mentioned above). Since the mesh was a little bit smaller than some of the turbid particles in the water, the manifolds would clog with the dirt particles. This was especially a problem when a high speed and volume of turbid water was passed through the bottom-most manifold during fluidization because it would cause the flow out of the pipe to be much lower than what was required to reach the necessary fluidization velocity. To remedy this problem, certain steps were taken before fluidization. The first step was to clean the bottom manifold by allowing the water already in filter to travel through the bottom-most manifold in the opposite direction that flow normally would pass through the manifold. This removed any large particles stuck inside the manifold and transported them out of the drain pipe (connected to the bottom manifold and located opposite the inlet) and back to the stock tank. Next, the filter was filled to the top with water with all of the inlets open to prevent the possible reclogging of the bottom manifold. During this time, the

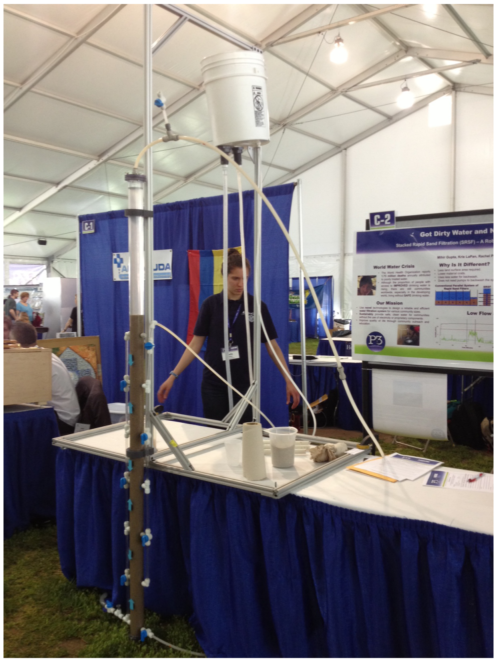

Figure 2: Small scale filtration unit at EPA competition.

backwash pipe is kept closed. Once the air valve on the backwash pipe began to fill up with water, the air valve was closed and the backwash pipe opened. All inlets remained opened until any remaining bubbles in the backwash pipe were pushed out of the system. Finally, all valves except the one at the bottom manifold were closed and the bed fluidized.

2.2 Manifolds

The manifolds for the filter needed to be redesigned due to a low resistance to stress. When in Honduras, the manifold branches were susceptible to breaking off the manifold stem due to the small connection surface area. To improve this connection, half inch slotted PVC pipes were connected using tee and cross connections in the same configuration as the original manifolds. Two of the seven manifolds have been constructed, except for the caps that close off the six branch pipes. The old design is shown below on the left in figure 3, while the new manifold is shown on the right.

2.3 Sand Drain

One of the main drawbacks of the first and second generation LFSRSFs was the removal of sand from the filter column. Once the sand was introduced into the

Figure 3: Design for old (left) and new (right) slotted manifolds.

filter, it is virtually impossible to remove without dismantling the entire unit. As a result, it was decided to place a sand drain on the side of the filter above the second inlet manifold from the bottom, within the fluidized sand layer. In order to remove the sand, the prototype will be operated in backwash cycle, and the backwash pipe will be closed. Prior to installing a sand drain, the only means for flow exiting during backwash was through the backwash pipe; however if the backwash pipe is closed then it forces the flow path out the sand drain. Since the location of the drain is low within the fluidized sand layer, nearly all the sand will be able to exit the filter in a sand-water slurry. See figure 4 for the proposed location of the sand drain on the LFSRSF and the current sand drain on the full scale SRSF in Tamara.

A preliminary model for calculating the sand drain was developed in Microsoft Excel which allows the user to change inputs such as height of the drain, pipe diameter, angle exiting the column wall, and separation distance between the valve and the filter column.This model calculates the height of sand removed from the filter as well as the height of sand remaining in the filter. The equations which were used include trigonometric functions such as sine and cosine. In addition, it determines whether the input parameters create a drain design which is allowable based on the geometric orientation of the drain with respect the ground. This is an important result because it needs to be easy for an operator to collect the sand slurry as it exits the drain; consequently there needs to be sufficient separation. Currently this Excel model is available through the shared network, in the Low Flow Stacked Rapid Sand Filter, Srping 2013 file.

The initial inputs for the sample design were as follows: Height of the drain = 30 cm, Pipe diameter = 2 inches, Angle exiting column = 60 degrees, and separation distance between the valve and the filter column = 3 inches. The model found this design to be acceptable. For this design, 102 cm of sand will be removed, and separation distance between the ground and drain of 7.3 inches.

Figure 4: Sand drain for full scale SRSF (right) and proposed sand drain location for LFSRSF (left).

3 Conclusions

The primary focus of in this semester was to design and construct a small scale filter which could be taken for demonstration purposes to the EPA P3 competition in Washington, D.C. The main issue faced during this process was the scaling down of the filter to an easily transportable device, while still keeping it large enough to maintain the underlying physics of the model. Fluidization was the determining factor in designing the flow rate required, while the cleaning capacity per depth of sand bed decided the height of the filter column. Another predicament faced due to scaling issues was the large number of valves that needed to be operated to switch the flow from filtration to backwash.

The small scale model at the EPA P3 competition won second place in the ASCE sustainable development award. The results of the EPA awards from the competition have not been announced.

In addition to constructing this model for the EPA, a new design for the manifolds for the full scale system was developed. The drilled-hole connections were replaced by cross- and T- connections to enhance the manifold's structural strength. A sand drain was also designed, but has yet to be incorporated into the full scale filter.

4 Future Work

4.1 Manifolds

Two newly designed manifolds have been produced, but the last five manifolds still need be constructed along with the addition of the end caps to the branched slotted pipes. Furthermore, the manifolds will be structural and hydraulically tested to ensure that the head losses through the manifolds at the given flow rate of 0.8 L/s are not so large that they cause the filter to fail.

4.2 Sand Drain

Now that there is a preliminary design for the sand drain, it will need to be tested and potentially modified based on how it functions. Implementation and testing of the sand drain will be dependent on the construction of a new lab filter, for which the drain will be incorporated into the new overall design. Testing will determine if the angle, length, and location of the drain are appropriate to achieve the required removal of sand from the filter, as well as if the design allows for easy capture of sand once it has been removed. Additional research on the most efficient and stable valve for use in the sand drain is also still required.

4.3 Construction Techniques & Ease of Operation

The new filter design will need to incorporate improvements to fabrication, including the specific techniques and materials used in the process. The goal will be to minimize the cost and increase the ease of fabrication of the filter. One component of fabrication which needs to be improved is the pipe drilling method that is used for the filter body. In Hondruas, the pipe for the filter body was cut on a drill press, and further research will need to be done to determine how this method can be replicated and improved. In order to minimize the cost of fabrication, possible alternatives for the cap design will also be investigated, due to the high expense of the current aluminum caps. There is potential to develop a cap design based off of the design that was used for the small-scale filter, which used a grooved cap made from a PVC plate and an o-ring to make it air tight.

There will also be further work done to improve the ease of operation of the low flow filter. Currently, an operator is required to turn three separate valves in order to switch the low-flow filter between filtration and backwash modes, as opposed to the one valve required for the full-scale. As evidenced by the performance of the small-scale (P3) filter, ease of operation becomes more difficult to achieve as the size and flow of the filter are scaled down, and further design research will need to be done to determine how hydraulics can be used to achieve the transition to and from backwash more easily at this scale.