Foam Filtration AguaClara Research Team

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Abstract

The Foam Filtration team is attempting to determine an application that utilizes polyurethane foam as a water filtration medium. Our work consists of running experimental trials which characterize the filtration properties of polyurethane foam. Polyurethane foam is not a conventional filtration medium, and through extensive work, we have proven that it can successfully produce effluent turbidities below US EPA standards. In addition to the characterization of foam as a filter medium, we have previously investigated the possibility of utilizing polyurethane foam at the point-of-use scale. A feasibility study determined that a polyurethane foam point-of-use unit would require the addition of coagulant and expensive moving parts. Therefore, the new focus of the Foam Filtration research team is on the design of an emergency water treatment system using polyurethane foam. This unit will consist of a roughing and finishing filter. Previous research characterized the performance of the finishing filter and current laboratory tests are focused on evaluating performance of the roughing filter.

Literature Review

Sobsey et al. [2008] evaluate different types of Ooint of Use (POU) systems available, which includes the system that uses coagulation. This was our main interest because our experimental trials with foam as a filter medium have shown that filter performance is only adequate with the addition of a coagulant. The authors scored POU systems requiring coagulation as 1 (the lowest on their effectiveness scale) because of the multiple steps the user would need to be familiar with in order for the system to work effectively. In addition to usability issues, economic concerns with coagulation at the POU scale are of interest. The cost of the coagulant would increase the material operating cost of the filter (which would otherwise be essentially zero) and would also increase the up- front cost of the unit itself. This prevents foam filtration from being a truly disruptive technology at the point-of-use scale, which is our goal in the design of a foam filtration unit. Because of this, our research was refocused on designing a multi-stage emergency filtration system.

The design of an emergency treatment unit has different considerations than a POU unit. Our current design consists of a roughing and finishing filter. Nkwonta and Ochieng [2009] evaluate the usage of roughing filtration technology as a pretreatment process. The article states that "roughing filtration may be considered as efficient pretreatment process in case surface water is used as water supply for treatment." Experimental trials with foam of relatively large pore size have shown that it does serve as an effective roughing filter, somewhat like the coarse-grained media used in traditional rouging filter designs. These results in combination with the evaluation of roughing filters for water treatment from Nkwonta and Ochieng [2009] suggest that it will make for a robust design for an emergency drinking water treatment technology.

Both natural and man-made disasters call for emergency treatment. "From a public health point of view, the (re-) establishment of a safe water supply is one of the three main interventions [for emergency relief], together with hygiene promotion and sanitation" [Dorea, 2009]. Thus, developing a low-cost, easily operable emergency drinking water treatment is of the utmost importance and has applications around the world. One particular application for this technology could be China. ZHANG et al. [2011] discuss the need for emergency treatment technologies due to the rapid industrialization in China which has led to frequent water pollution accidents.

Background

Potential Applications of Foam Filtration

The AguaClara Foam Filtration team is currently investigating the filtration properties of polyurethane foam. Research beginning in the Spring of 2011 has proven that polyurethane foam is an effective filtration medium; influent waters below 10 NTU can be treated to meet EPA effluent standards of 0.3 NTU. These trials were conducted using a coagulant feed (alum) which significantly improved filtration performance. Though Foam Filtration was originally investigated for application at an AguaClara plant, feasibility analyses of a full scale foam filter have shown that it would be extremely labor intensive to operate a foam filter in a municipal-scale plant because there is no known way to have a mechanized backwash/cleaning cycle. Since Foam Filtration technology was shown to be viable, the Foam Filtration team moved to the design of a Point-of-Use (POU) unit, which would be easier to operate and clean.

In the Spring of 2011, the Foam Filtration team began the design of a POU Foam Filtration unit. Plans for this unit included both an a coagulant and chlorine doser; however calculations proved that dosing at such a small scale was impractical. It was important to not include any moving parts (e.g float valves), which further complicated the dosing design. A very important factor in the design of the POU unit is the usability in comparison to other POU devices currently available. Because there are POU devices that do not require a chemical feed and are not operated on a batch system, it is a priority that the Foam Filtration POU unit also have these qualities.

Because Foam Filtration was initially evaluated with the assumption that a chemical feed would be available, it is now necessary to conduct a series of experiments evaluating the filtration performance of foam without a coagulant feed. Experimental trials conducted in the Summer of 2010 showed that at an approach velocity of 6 mm/s, foam filtration can reduce influent turbidities of 5 NTU to 1 NTU (Figure 1 on the following page). Though this performance is not as good as filtration that utilizes an alum feed, dosing presents complications in the design of a POU unit.

It is postulated that a reduction in approach velocity from 6 mm/s (the optimal approach velocity for foam with the influent dosed with alum) to 1 mm/s could result in acceptable filtration performance. The foam depth will be kept at 10 inches, the optimal value found from previous research. Through the results of this experimental trial, the Foam Filtration team would like to continue with the design of a POU Foam Filtration unit that will be easy to operate and will not require the addition of any chemicals.

Polyurethane foam for roughing filtration

A roughing filter is usually used as part of a multi-stage filtration system to initially filter turbid water as well as to aid in flocculation. Typically a roughing filter is composed of gravel or other larger particles while the finishing filter is composed of sand or other finer particles. Previous experiments in spring of 2011 have shown that 30 ppi foam, while not as effective as 60 or 90 ppi foam at treating turbid water, does not cause as much head loss in the filtration column and is thus less likely to collapse when filling up with clay. This would make 30 ppi foam ideal for a roughing filter that would need to be deeper than a typical finishing filter. Foam would also be ideal for a multi-stage filter in an emergency setting because it is durable and much lighter than gravel and sand, making it much more robust and portable.

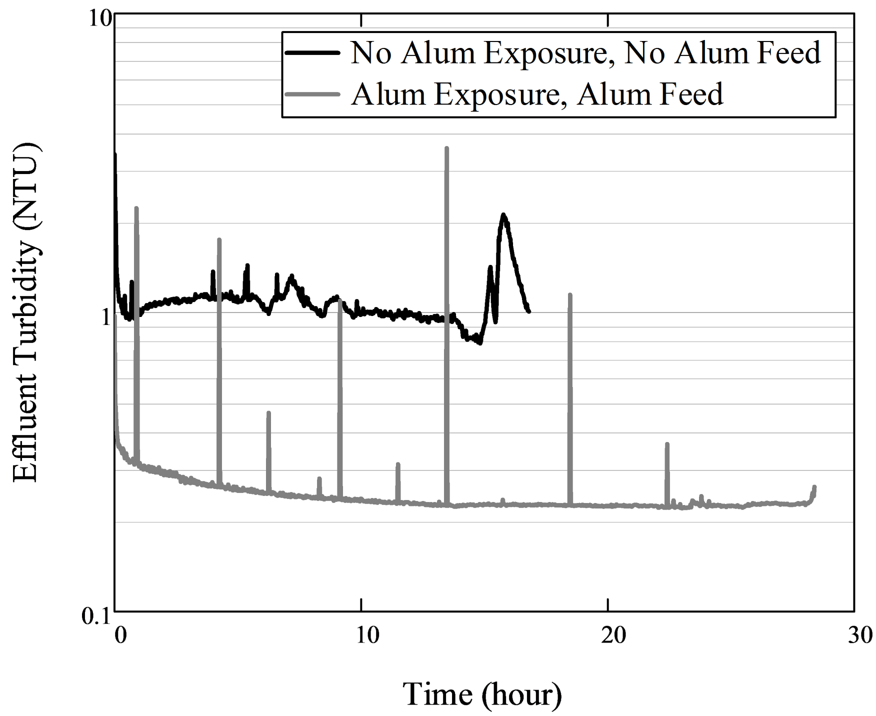

Figure 1: Performance of 90 ppi foam with an approach velocity of 6 mm/s with no previous alum exposure, and no alum feed and alum exposure, an alum feed of 1.5 mg/L and an influent turbidity of 5 NTU.

Experimental Methods

Bench-scale apparatus description

In order to analyze the effectiveness of foam as a filtration medium without a chemical coagulant, a simplified version of the foam filtration experimental apparatus from the Spring of 2011 was developed. Like the previous apparatus, the influent was a suspension of concentrated clay particles in temperature-controlled, aerated tap water. The influent was maintained at a constant turbidity by Process Control software that compared the average of five seconds of turbidity readings to a user defined value. When the turbidity fell below the desired value, an automated pinch valve would open allowing a small amount of concentrated clay stock suspension into the raw water mix. The flow rate of the influent was controlled manually by a peristaltic pump (Cole-Parmer Masterflex) with variable speed and was set to have a $1\frac{mm}{s}$ approach velocity through the filter column. The pumped suspension was gathered in a flow accumulator before continuing on to the filter apparatus to reduce pulsing caused by the pump. The filter apparatus was composed of a 1 inch diameter glass tube approximately 2 feet in length. The filter media used was 90 pore per inch (PPI, a linear measurement) polyurethane foam cut into 10 cylinders, each approximately 1 inch in height and slightly larger than 1 inch in diameter. It was necessary to cut each foam cylinder slightly larger than the diameter of the glass tube to slightly compress the foam in the filtration column and thereby prevent preferential flow paths along the walls of the column. Each piece of foam was carefully squeezed underwater before being transferred to the filtration column, and was squeezed again inside the column to release any air trapped within the foam. Air bubbles caught within the filter media effectively reduce the filter surface area, driving up the approach velocity and reducing performance. The turbidity of the effluent was then measured and recorded by the Process Control software before the effluent was emptied down a drain. A detail of the experimental apparatus is shown in Figure 2.

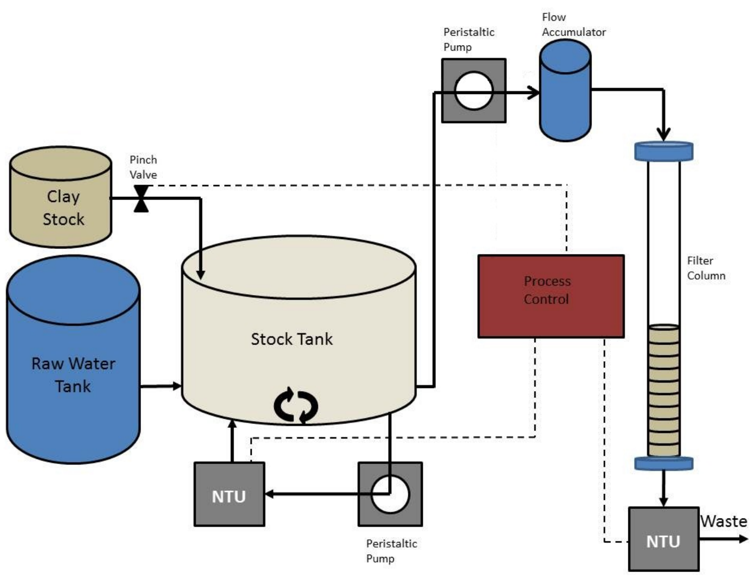

Figure 2: An overview of the experimental apparatus without coagulant dosing

Data collection and analysis

The results of our experiments are quantified by comparing the filter influent and effluent turbidity, measured by data-logging inline turbidimeters (MicroTOL, HF Scientific). A filter run is considered successful for the amount of time that the effluent turbidity falls below 0.3 NTU, the US EPA standard. This standard allows for easy comparison between filter runs of different conditions. Additionally, log removal (pC*) is also a metric for determining filter performance; however, when influent turbidities are varied, it is more straightforward to compare effluent turbidity.

Log removal is defined as the negative log of effluent turbidity divided by influent turbidity.

Setup of bench scale experiments

Based on our earlier results showing that foam needed a chemical coagulant to be an effective filter media, we began designing a foam roughing filter that could be used in emergency scenarios as part of a small scale transportable multi-stage foam filter. The difference between this experimental set up and the past semesters experiments are that this time we are also switching to PACl from Alum because PACl works better as a coagulant and costs less to achieve the same coagulation performance. We are also interested in measuring the head difference when the effluent turbidity becomes the same as influent turbidity. We are starting with 100 NTU as the influent turbidity. Refer to Figure 3 below for further description of the apparatus.

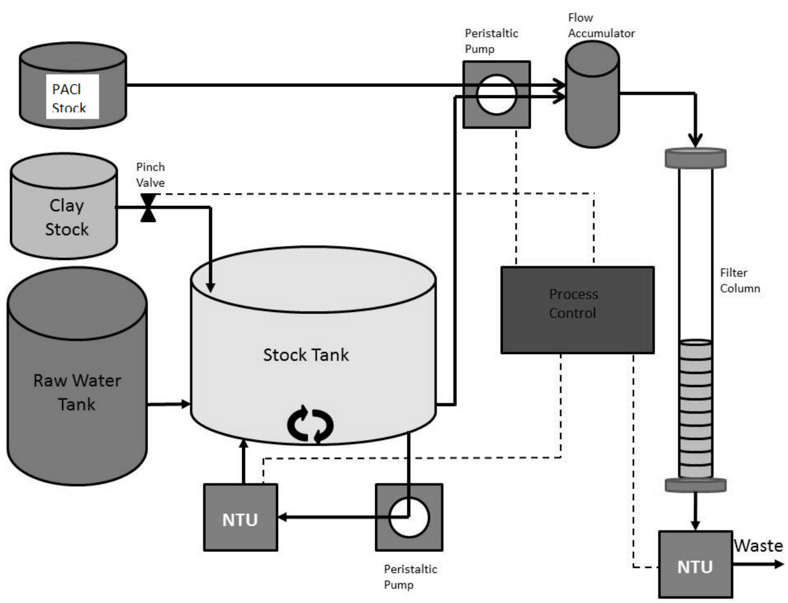

Figure 3: An overview of the experimental apparatus with coagulant dosing

In order to continue our explore the idea of using foam with a larger pore size as a roughing filter, we also decided to investigate the relationship between the depth of the foam filter bed and its performance. The experimental apparatus is the same was was previously described; however, we increased the approach velocity to 6 mm/s and varied the depth of foam. Bed depths of 5, 10 and 15 inches were chosen. This range will accurately capture the effect of filter bed depth on performance. This experimental trial will also give insight into the filter bed capacity for capturing particles. Additionally, 30 ppi foam filtration performance was measured as a function of varying influent turbidity. The same experimental apparatus was also used for this trial, however the PACl dose was varied linearly to reflect the differences in influent turbidity. Research in coagulation has shown that for a 100 NTU influent, a PACl dose of 8.33 mg/L is appropriate. Based on this, the PACl dose was varied linearly to reflect different influent turbidities (i.e. a 50 NTU influent would require a PACl dose of 4.17 mg/L).

Experimental Analysis

Foam filtration performance with no coagulant

Our first experimental trial was to test the performance of 90 ppi foam without a coagulant. The purpose of this experiment was to determine whether or not a point-of-use filter unit could be operated without the addition of a coagulant. The addition of a coagulant is an important design consideration, since calculations from the Spring of 2011 proved that chemical addition at the point-of-use scale is not practical without the use of expensive parts (i.e. float valves) or a very dilute stock concentration. Therefore, using polyurethane foam on the point-of-use scale is impossible from a practical standpoint if coagulant must be added. Filtration performance without the addition of coagulant is shown in Figure 4.

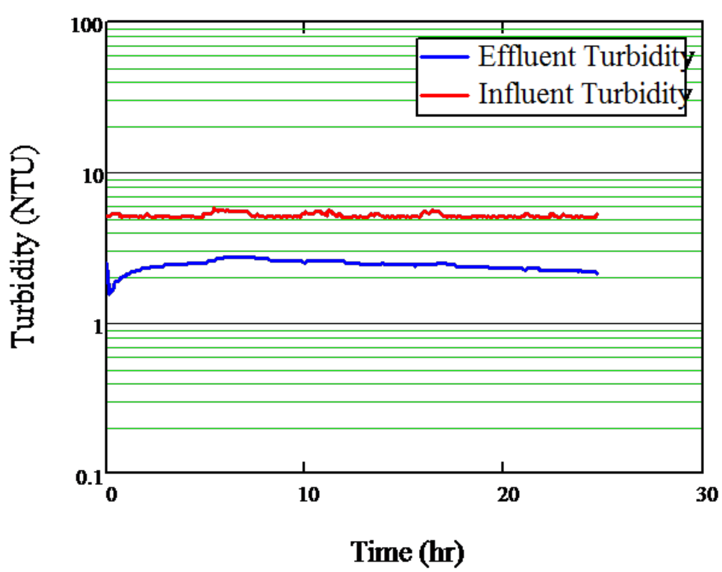

Figure 4: Performance of 90 ppi foam with an approach velocity of 1 mm/s with no alum feed and a 5 NTU influent

The effluent turbidity does not reach 1 NTU at any point throughout the experimental trial. This turbidity is far above the US EPA standard of 0.3 NTU. Additionally, it should be noted that the approach velocity in the filter was decreased from 6 mm/s to 1 mm/s in hopes of improving filter performance. Even with the significant decrease in approach velocity, the effluent turbidity still did not reach desirable levels. Thus the idea of foam at the POU scale was abandoned and we refocused on utilizing polyurethane foam for an emergency unit, which is at a slightly larger scale and would allow the use of more sophisticated chemical dosing.

Characterization of foam for roughing filtration

The proposed emergency system will use two pore sizes of foam: 30 ppi and 60 ppi. The 30 ppi foam will act as a roughing filter and the 60 ppi as a finishing filter. Filtration performance of 60 ppi foam has been characterized in previous research. However, 30 ppi foam must be tested to prove that it can act as an effective roughing filter. Previous semesters' research had eliminated 30 ppi for use in the POU filter; however, if the 30 ppi foam can bring effluent turbidities down to approximately 10 NTU, the finishing filter can produce acceptable effluent turbidities for drinking water.

The first experimental trial using 30 ppi was to determine the relationship between filter performance and filter depth. Filter depths of 5, 10 and 15 inches were tested and the results are shown in Figure 5.

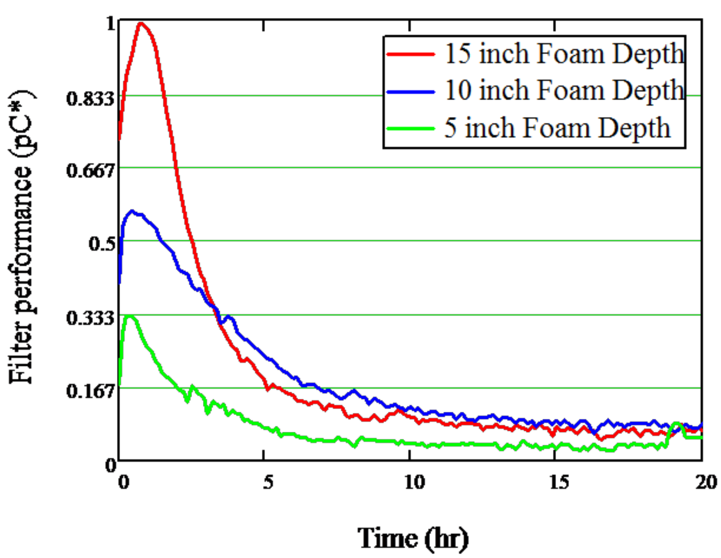

Figure 5: Filter performance of 30 ppi foam with an approach velocity of 6 mm/s, an alum feed, a 100 NTU influent and a 5, 10 and 15 inch filter bed depth.

These results prove that filtration performance is directly related to the depth of the filter, as is expected for a depth filtration process. Since the 15 inch foam depth can successfully filter 100 NTU water to 10 NTU, it is assumed that a filter bed of approximately 30 inches will be able to perform at least as well, and thus the roughing filter will be able to provide acceptable influent turbidities for the finishing filter. Additionally, it should be noted that when the pC* data is normalized with the bed height, all three performance curves are the same. Thus, filtration performance varies linearly with filter bed depth, and based on the desired effluent turbidity, the bed height can be determined. The normalized filter performance data is shown in Figure 6.

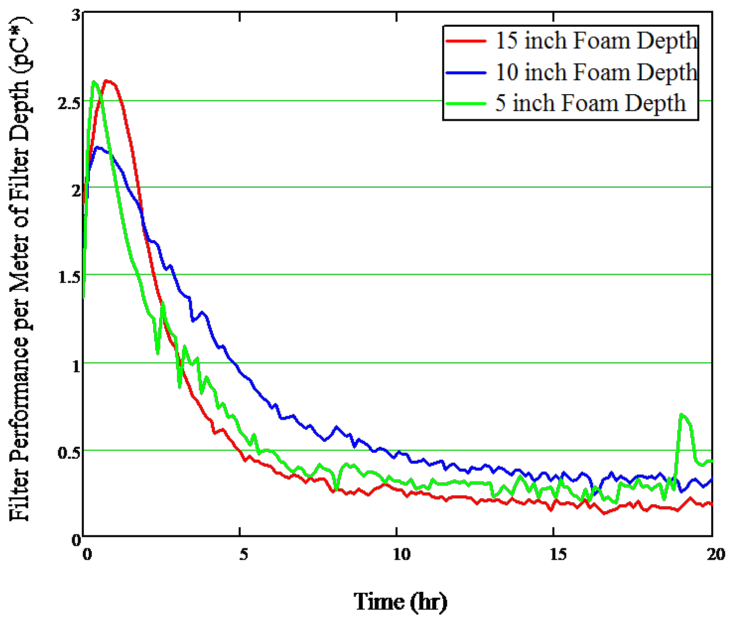

Figure 6: Filter performance of 30 ppi foam with an approach velocity of 6 mm/s, an alum feed and a 100 NTU influent, normalized with respect to filter depth

Additionally, head loss was monitored throughout the 30 ppi experimental trial. Measuring the head loss throughout a filter run is extremely important for the design of the emergency filter unit. The head loss was found to vary linearly up to about 0.007 cm with respect to run time as particles accumulated in the filter bed, consistent with previous head loss measurements for 60 and 90 ppi foam and with general depth filtration theory. It is important to note that head loss is negligible in its overall magnitude throughout the filter run, and thus filter bed head loss with 30 ppi does not need to be considered when designing the filter unit.

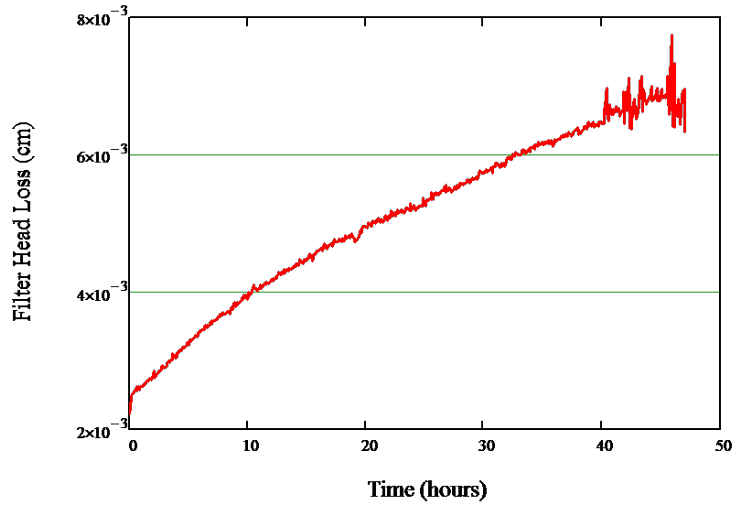

Figure 7: Head loss through the Filter Column of 30 ppi foam, 6 mm/s, alum, and 100 NTU influent

The last set of experiments we ran this semester was to investigate the filtration performance with varying influent turbidity of 100, 50 and 25 NTU. For each different influent we varied our PACl dose accordingly when we ran the experiment.

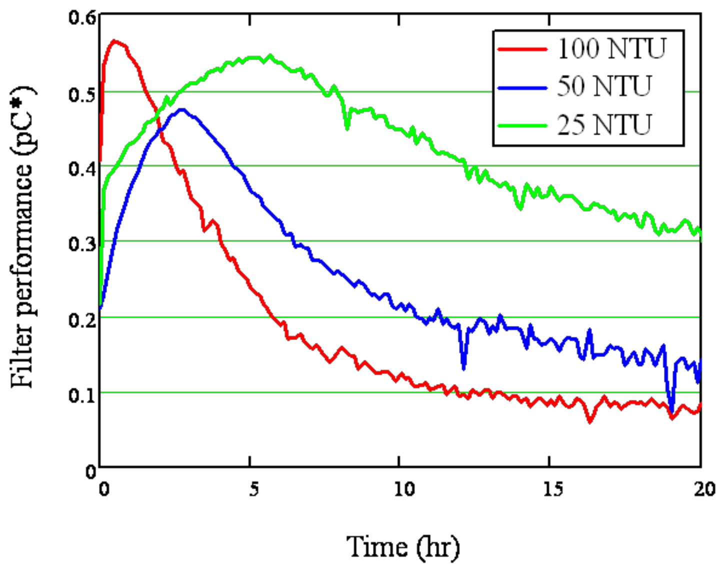

Figure 8: Filter Performance of 30 ppi foam with an approach velocity of 6 mm/s, an alum feed with varying NTU of 100, 50, and 25

As the graph shows 30 ppi foam showed a more stable and expected result for 100 NTU influent. We can also see that the performance of the filtration for NTU of 25 is far better than the performance of 100 NTU, However, with the 100 NTU influent the filter performs well enough, bringing down the NTU to approximately 30 NTU which further confirms that 30 ppi foam has a potential to be used as a roughing filter.

Design of Emergency System

Arrangement of roughing and finishing filters

The emergency filtration system is set up as a multi-stage filtration unit. One roughing filter is followed by two finishing filters operated in series. The unit will have two finishing filters operating in series for two reasons. First, two finishing filters ensure that the filtration system is always running, even during the cleaning cycle for one of the finishing filters. During cleaning, one of the finishing filters may be bypassed and this will not result in a deterioration of effluent quality. The schematic is shown in Figure 9. The x's represent where valves will be located in the system.

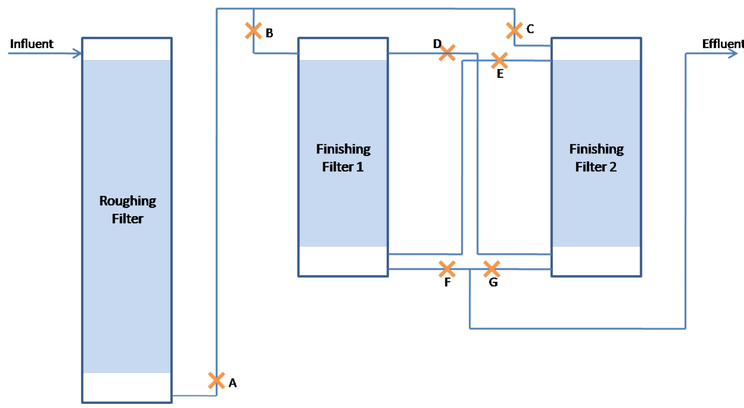

Figure 9: Preliminary filter schematic for emergency system

The filter has four modes of operation and are described as follows:

1. Both finishing filters are in operation. Order of operation is Filter 1, Filter 2 and valves A, B, E and G are open.
2. Finishing filter 2 is in operation while finishing filter 1 is offline for cleaning. Valves A, C and G are open.
3. Both finishing filters are in operation. Order of operation is Filter 2, Filter 1 and valves A, C, D and F are open.
4. Finishing filter 1 is in operation while finishing filter 2 is offline for cleaning. Valves A, B and F are open.

Design of emergency system cleaning mechanism

In addition to experimentally determining the filtration properties of polyurethane foam, it is also important to work toward the design of the filter unit itself. Perhaps one of the biggest challenges is to design a cleaning mechanism for the foam. Unlike sand, there is no conventional backwash method, and on the laboratory scale, the foam is cleaned similarly to how a kitchen sponge is cleaned. With this in mind, a plunger system was devised that will clean the foam in situ. When cleaning the foam, the primary constraint is to ensure that no air bubbles are trapped in the foam. This essentially decreases the surface area of the filter bed and increases interstitial velocity, which will reduce filtration performance. When designing the plunger system, it is important that the foam be submerged at all times. This is the simplest way to ensure that no air bubbles are trapped in the foam. A schematic of the preliminary design is shown in Figure 10. It should be noted that the plunger consists of a firm piece of plastic that is either porous or has holes drilled in it.

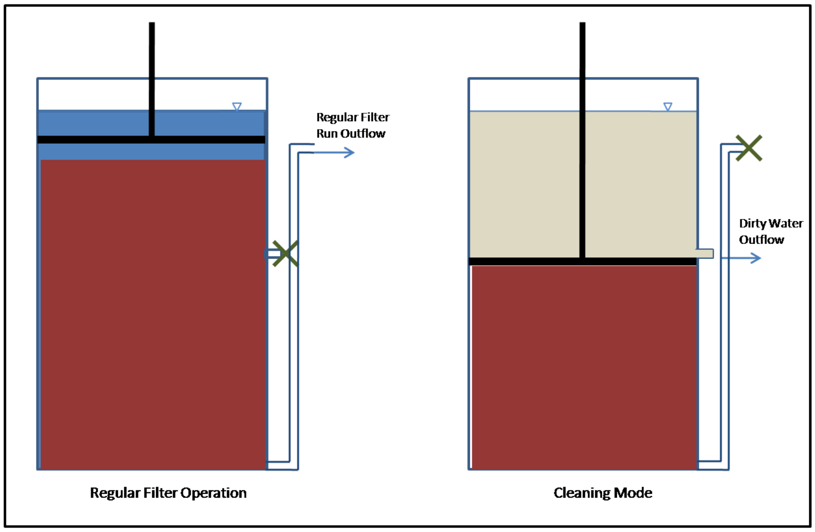

Figure 10: Foam filter proposed cleaning mechanism, during regular filter operation and cleaning

The proposed method of operation is as follows:

1. When the foam is ready to be cleaned, attach the plunger apparatus to the top of the filter bed. Compress the foam to the level specified by the plunger. There will be a block that will not allow the user to lower the plunger any further

2. Drain the dirty water released from the compressed foam from a valve that is located above the height of the foam. The valve must be placed such that the level of the compressed foam is always below the valve height. This ensure that the foam remains submerged during the cleaning process.

3. While the foam is still compressed, close the valve on the side of the filter unit and fill the foam unit with clean water. Let this drain out the bottom exit channel so that the foam can be rinsed by one pass of clean water.

4. Fill the filter unit with clean water once again and release the plunger, allowing the foam to return to its pre-compressed height and resume filter operation.

This proposed cleaning mechanism has yet to be tested. It will likely be modified after such tests to produce the cleanest foam while using the least amount of clean water.

In addition to developing a cleaning mechanism for the foam unit, it is also important to design the plumbing that will connect the two filter beds (roughing and finishing). Care must be taken to ensure that the plumbing does not induce excess head loss and uses as few valves or other expensive parts as possible.

Conclusions

Based on our experimental results, our initial design of a POU scale foam filtration system without a chemical coagulant additive seemed to be unreasonable. The foam filter proved to be too inefficient without a chemical coagulant even at very slow approach velocities. The addition of a chemical coagulant would undoubtedly make filter performance acceptable; however, the addition of coagulant to the filtration design would significantly increase the cost of the POU unit and would additionally make the unit more difficult to operate. The goal in the development of foam filtration POU unit was to have the technology be disruptive- this unit would have to be both cheaper and easier to operate than other POU units currently available and gain a large 'market share' in the POU sector. However, with the necessity of adding coagulant, a POU foam filtration unit can no longer be a disruptive technology. Therefore, since it has been shown that polyurethane foam can successfully treat water, our team wanted to find an appropriate use for this technology and, the idea of using polyurethane foam for emergency treatment was developed.

Previous research has characterized the filtration performance of the finishing filter for the emergency system. Research characterizing the roughing filter has proven that 30 ppi foam can effectively treat highly turbid (100 NTU) water to levels that would not overwhelm the finishing filter. Additionally, the head loss through the roughing filter is so minimal that collapse of the roughing filter is not a failure mechanism of concern. This is very important in the design of the emergency system, as previous research has proven that foam collapse leads to irreversible damage to the foam resulting in decreased filter performance. Knowing that collapse will not occur in the roughing filter will simplify operating constraints and make the filter easier to maintain.

Future work

Since utilizing foam in a POU device proved infeasible, we have begun designing a larger-scale emergency foam filtration system that would ideally fit into the bed of a pickup truck. Experimental results have shown that 30 ppi foam serves as an effective roughing filter. The relationship between depth and roughing filter performance has been quantified as well as the relationship between influent turbidity and roughing filter performance. This is essential for operation of the emergency filter in the field, and will be used to develop user instructions for the filter unit.

In addition to the experimental work, it is also important to continue working on the design of a prototype. Preliminary design plans for the foam cleaning mechanism have been developed and the plunger system has been built for a 5 gallon bucket. Additionally, the plunger has been built for a filter unit with a 4 inch diameter. Testing this system is the next step that must be completed. Different methods of operation will be tested to find the best way to clean the foam in situ. While the foam cleaning system is being optimized, plumbing for the filter unit must be designed. Head loss through pipes and minimization of expensive parts such as valves are two important design considerations. Once the plumbing has been designed, construction of the entire unit can begin.

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