Turbulent Tube Flocculator

Felice Chan, Brooke Pian, Amanda Rodriguez, Greta Schneider-Herr

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1 Literature Review

The purpose of our team's research is to design and implement a lab-scale turbulent flow flocculator because full-scale AguaClara plants use turbulent flow flocculators, and current research has only been performed with a laminar flow flocculator.

Significant factors in flocculation are energy dissipation rate, time through the flocculator, fraction of the total volume occupied by flocs, attachment efficiency, and fractional coverage of a colloid surface by coagulant (Weber-Shirk)[8]. Previous research has found that large eddies dissipate a small amount of energy. Instead, most of the energy is dissipated by viscous forces in turbulent flows. Other variables influencing flocculation are particle size distribution and density, temperature of the fluid, and the reactor's mixing time and intensity (Casson and Lawler, 1990)[2].

The current tube flocculator set-up has a water intake and coagulant metering system, rapid mixing and tube flocculation, as well as a flocculation residual turbidity analyzer (FReTA) under laminar flow conditions (Fleming and Li, 2013)[3]. Our goal is to extend our laminar flow models in order to study turbulence and the effects of various energy dissipation rates on overall flocculation performance by designing and constructing a turbulent flow flocculation apparatus.

In "Tube Floculator Team Research Report," Fleming and Li found that "ideal test conditions are the more typical full scale plant operating conditions." This design seeks to create test conditions modeled as close as possible to the plant conditions. This condition will help to create efficient flocculation using low Reynolds number turbulent flow and varying energy dissipation rates to examine the predictive flocculation model hypothesis that "large particles are useless" (Swetland et. al. 2012)[7] and to inspect the effect of a varying energy dissipation rate. Theoretically, varying the energy dissipation rate should allow better control of floc creation. This is because there is a balance between the fact that effluent turbidity decreases with increasing average energy dissipation rate, which leads us to design with high energy dissipation rate, and that when the dissipation rate is too high, flocs are broken up to the point that they are not captured by the sedimentation tank, causing us to design with a lower average energy dissipation rate. By varying the dissipation rate along the apparatus, these opposing design constraints can be optimized.

The main variables that need to be determined for this set up are optimal number of floc break up devices, the constriction magnitude of these devices, and the flow rate and the pipe diameter needed to maintain turbulence. In general there are two methods to create flocculation in a pipe: flow expansions/contractions around obstructions in the pipe such as baffle or beads and constrictions of the flow caused by differences in the inner diameter of the pipe. Unlike previous AguaClara designs, the ability to vary the energy dissipation rate down the experimental set up is of key importance. This will be done by the use of a clamping device that can be adjusted to give the desirable energy dissipations. Previously established optimums for flocculation efficiency were used including an optimal H:S ratio of 4:1 which corresponds to the highest possible flocculation efficiency and energy dissipation rate.

Because of the length of the design, it is possible that the head loss will be significant. The design reflects this constraint.

Another design component is the construction of a clear column for use of imaging floc particles at the end of the apparatus. Of key importance is that the transition from piping to the imaging column does not affect the structure of the flocs.

2 Introduction

The inclusion of this team was prompted by our lack of detailed understanding of turbulent flow models. Current research and apparatus have been applied to laminar flow regimes. However, flocculators in full-scale AguaClara plants demonstrate turbulent flow. As such, the completion of our challenge will benefit AguaClara and our mission of providing safe drinking water by extending our knowledge of flocculation to different hydraulic regimes, improving the design and efficiency of AguaClara technologies.

3 Methods

3.1 Flocculator Design

3.1.1 Preliminary Flocculator Design Ideas

Originally, the team had an estimate that the total length of the flocculator would be about 100 meters in length with an inner diameter of about 3.5 centimeters. Because of this, the team thought that the size of the flocculator would be a major problem and considered several options to minimize the space it would occupy.

Since the laminar flow flocculators in the AguaClara Labs now are either coiled or looped in a figure 8, the team decided coiling it would be a good way to conserve space. However, if the flocculator were to be 100 meters, even a coiled flocculator would be huge, so the team considered putting a coil within a coil.

Another design idea was to have a coiled horizontal flocculator, like the current setup of the flocculators in the AguaClara Lab. However, this idea was also abandoned because it would be more difficult to support the horizontal flocculator so that it would not collapse on itself.

3.1.2 Preliminary Clamping Ideas

The team considered several options for creating constrictions as well. The main factors considered were the cost, ease of construction, and the ability to change the constrictions for different energy dissipation rates. The team also wanted to create rounded constrictions, as opposed to sharp constrictions, so that the flow in the tube would be smoother.

Zip ties were considered but it was determined that zip ties would not be strong enough to constrict the tubing the desired amount. Hose clamps were also considered but it was decided these would not be as cost efficient. A list of clamps considered are shown in table 2

One idea was to put a string of beads in the flocculator that would take up 60% of the total cross sectional area of the tube. An general example of this is shown in 1. The team determined that this would be inefficient because if one bead broke, or moved out of place, it would be extremely inefficient to replace the one bead. It would also be difficult to string beads into the tubing in the first place.

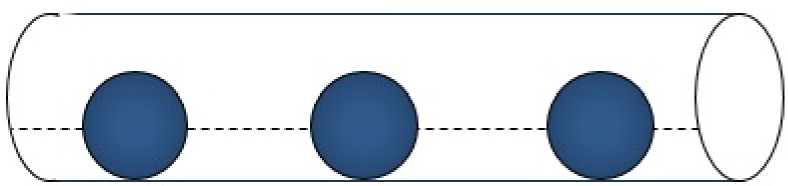

Figure 1: Beads

The team considered using C-clamps and clamping the tubing from the outside at the calculated interval. The team would also be able to easily adjust for different energy dissipation rates and replace the C-clamps. However, C-clamps are 1 to 2 dollars each, and about 1000 clamps would be needed, it would be a very expensive option.

3.1.3 Final Design Ideas

The final design idea is to have a single coiled vertical flocculator. After doing calculations for the actual dimensions of the flocculator, the team realized that only about 60 meters of tubing would be needed, almost half of what was originally anticipated. Therefore, the double coil would not be necessary.

The final clamping idea was to use rods of the same inner diameter of the tubing to externally clamp the tubing on both sides. The rods would be efficient so the team would not have to individually clamp the tubing at the calculated interval, and the size of constriction would be relatively easy to adjust if the desired energy dissipation rate were to change. The team calculated that 12 constrictions (24 rods) would be needed to create the appropriate constrictions.

Because the coils would be sitting on top of each other, another concern was that the weight of the tubes would cause the tubing to collapse on each other. To resolve this, the team considered using wiring ducts and cutting out two spaces between each duct creating a ladder-like apparatus so that each coil could sit on the duct and not on each other. A general schematic of this design is shown in figure 3. The figure is a cross sectional view of what the flocculator is anticipated to look like. Figure 2 shows a top view of the flocculator.

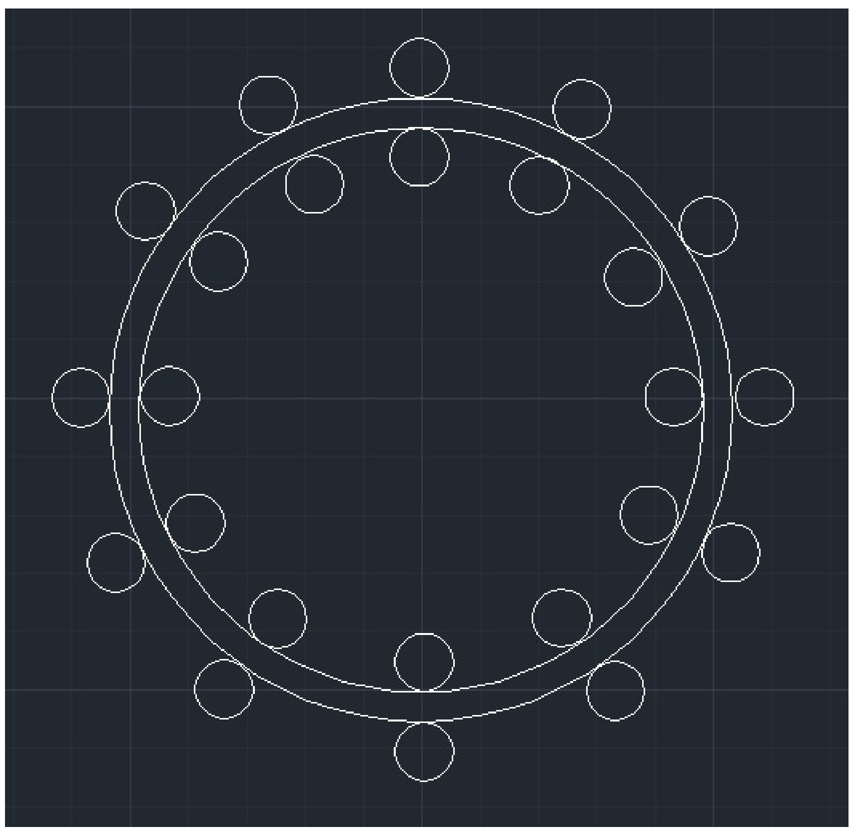

Figure 2: Top View of Flocculator

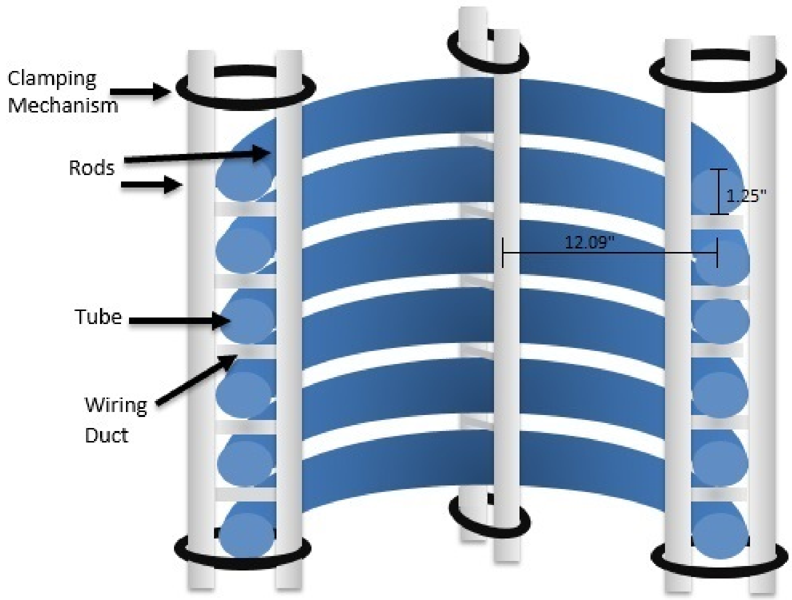

Figure 3: Flocculator Design

3.2 Materials

3.2.1 Preliminary Tubing Options

The team did extensive research on different tubing, clamping and coiling options. The tubing was researched based on calculations from CEE 4540 notes. Components for the design of the schematic were preliminarily sourced. The different tubing and clamping options found are displayed in table 1 below.

Table 1: Tubing Options

Material	Inner Diameter (in)	Cost per foot ($)
Clear PVC	1.5	4.24
Clear PVC	1.5	9.04
Braided Poly	1.5	16.28
Poly	1.05	1.57
Neoprene	2	8.64
PVC	1.59	5.16
Reinforced PVC	1.5	5.12
Reinforced PVC	1.25	4.04
Local Finger Lakes Extrusion Company (585) 905-0632		
PVC	1.25	2.86
PVC	1.5	3.05
PVC	1.5	4.2
Reinforced Vinyl	1.5	3.15

For piping options, all accessible online catalogs were scoured for optimal tubing. The cost per unit length, inner and outer diameter, composition, and length sold of fourteen different tubing was compared. The ClearFlex brand which happens to be extruded locally by Finger Lakes Extrusion was cheapest per unit length. The company was contacted via email and phone to learn more specifics. Finger Lakes Extrusion can custom extrude any combination of inner diameter, wall thickness, and length that the customer requires. After they set up the equipment, it takes about three hours to extrude and two hours to cool, so it can be shipped the next day. The tubing can be coiled any way that the customer desires, including on cardboard or plastic tubing and in varied coiling configurations. Flexibility varies, with the schedule of the tube, but it is similar to IV tubing used in hospitals, and should be perfect for the design.

However, the team ultimately decided to purchase tubing from US Plastics because it is cheaper and it would be faster to order premade tubing rather than having it custom made.

3.2.2 Preliminary Clamping Options

While the team was considering clamping ideas, research on the materials was done. Two main situations are proposed for the design: a system where one individually changes constrictions by hand and a system where long rods allow for a gradual change in constriction. The options we researched for clamps are shown in the table below 2.

Table 2: Clamping Options

Type of Clamp	Size (in)	Cost per Clamp ($)
C-clamp	2.0	2.26
C-clamp	1.5	2.65
C-clamp	2.0	2.50
C-clamp	1.0	1.70
C-clamp	2.0	1.70
Hose Clamp	1.0-2.0	1.18

3.2.3 Purchased Materials

The team ordered 60 meters of clear, flexible PVC tubing from US Plastics. The tubing came in four pieces of 50 feet each. The inner diameter was 1.25 inches, the outer diameter was 1.4375 inches and the wall thickness was 3/32 inches. The product number from US Plastics was 413905.

Free samples of wiring ducts were sent from McMaster-Carr to see if they would actually work to hold up the coils of tubing. It was determined that snapping out two of the ducts would create enough space to fit and support the tubing so the wiring ducts will be purchased.

3.2.4 Additional Materials Needed

There are still several things that need to be purchased:

1. Thin tubing to connect pieces of flocculator: Because US Plastics does not sell 60 meters of continuous tubing, the tubing arrived in four separate pieces. To connect them, the flexible tubing of the flocculator will be stretched over a thin-walled piece of rigid tubing. A list of possible tubing options are shown in table 3.

Name	Inner Diameter (in)	Wall Thickness (in)	Length (ft)	Price ($)
Rigid Aluminum Tubing	1.18	0.035	1	6.67
Smooth-Bore Seamless Stainless Steel Tubing	1.245	0.065	1	26.81
Multippurpose Aluminum Tubing	1.18	0.035	3	16.13

Table 3: Thin Tubing for Connecting Tubes

2. Rods to create constrictions: The rods to create constrictions also need to be purchased. Rigid PVC tubing was considered but the problem with

using PVC is that it bends so the team has been looking at using aluminum tubing on McMaster-Carr because it is a relatively cheap metal. A list of possible options is shown in table 4.

Name	Inner Diameter (in)	Wall Thickness(in)	Length (ft)	Price
Ultra-Corrosion-Resistant Architectural Aluminum	1.37	0.065	8	23.38
Rigid Aluminum Tubing	0.93	0.035	6	16.66
Rigid Aluminum Tubing	1.18	0.035	6	19.06
High-Pressure Welded Steel Tubing	1.12	0.065	6	22.98
Multipurpose Aluminum Tubing	1.18	0.035	6	26.01
Multipurpose Aluminum Tubing	0.834	0.083	6	37.53
Multipurpose Aluminum Tubing	0.87	0.065	6	30.1

Table 4: Rigid Tubing for Clamping

3. Wiring Ducts to hold up coils: The team received free samples of wiring ducts from McMaster-Carr and determined that the one with a width of 1.5" and a height of 3" with a slot width of 0.31 inches would work. The Wiring ducts are sold in lengths of 6 feet 6 inches so it should be long enough for the height of the flocculator.

Name	Width (in)	Height (in)	Length	Slot Width	Price
PVC Wire Duct	1.5	3	6'6"	0.31"	38.33

Table 5: Wiring Ducts

4. Hose Clamps or Long Screws/Bolts to hold the rods together: The team is considering using hose clamps or a long screw to hold the rods together. Table 6 shows possible hose clamp options.

Name	Clamp ID Range (in)	Band Width (in)	Package Quantity	Price ($)
Worm-Drive Hose and Tube Clamps	3.31-4.25	0.5	10	11.05
Worm-Drive Hose and Tube Clamps	3.31-4.25	0.5	5	7.92
Worm-Drive Hose and Tube Clamps with Nonslip screw	3"-4	9/16	5	10.43
Type 316 Stainless Steel Smooth Band Worm-Drive hose and tube clamps	3-4		1	6.06

Table 6: Hose Clamps

The team also considered using long screws or bolts to connect the rods. A list of possible options is shown in table

Name	Length (in)	Threaded	Package Quantity	Price
Extreme-Strength Steel–Grade 9	6	Partially	1	3.34
High Strength Steel–Grade 8	5.5	Fully	5	14.7
Round Head Square Neck Bolts	6	Fully	1	2.49
Medium-Strength Steel—Grade 5	6	Partially	10	5.30
Low Strength Steel	6	Fully	25	6.96

Table 7: Long Screws and Bolts

5. Solenoid Valve: A new solenoid valve with an orifice diameter of 3.456 mm needs to be purchased. The calculations for the diameter of the solenoid valve are shown in section 3.3.3. A list of possible solenoid valves are shown in table 8.

Name	Orifice Diameter (in)	Valve Design (in)	Valve Configuration	Max. Pressure (psi)
Solenoid Valve, 2/2, 1/4 In, NC, 24V, Brass	5/32	2-way	Normally Closed	63
Catalog No. 8262H187 24/DC (from ASCO valve)	5/32	2-way	Normally Closed	135
Catalog No. 8262H208 24/DC (from ASCO Valve)	7/32	2-way	Normally Closed	35

Table 8: Solenoid Valves

3.3 Calculations

3.3.1 Initial Design Parameters

The team derived the following three formulas from CEE 4540 notes to find the dimensions of the smallest turbulent flow flocculator. Because the formulas in the notes were for a rectangular flocculator, the team altered them for a circular tube. The three formulas are shown below, where $H_{tube}$is the height of the constricted tube $ID_{tube}$is the inner diameter of the tube, Rey, Reynolds number, is 4000, ν,viscosity, is $1\frac{mm^2}{s}$, K_b, the baffle coefficient is 2, $\Pi_{HS}$is the $\frac{H}{S}$ ratio, which is 4.

$$H_{tube} = \frac{1}{5}(5 \cdot ID_{tube} - \sqrt{10} ID_{tube} \tag{1}$$

$$ID_{tube} = \left[\frac{(Rey \cdot \nu)^3 \cdot K_B}{\Pi_{HS} \cdot \varepsilon_{tube}}\right]^{\frac{1}{4}} \tag{2}$$

$$Q_{plant} = \frac{\pi}{4}\left[\frac{(Rey \cdot \nu)^7 \cdot K_B}{\Pi_{HS} \cdot \varepsilon_{tube}}\right] \tag{3}$$

The team solved these equations using three different target energy dissipation rates of 10, 20 and $30\frac{mW}{kg}$ and a target Reynolds number of 4000. The results are summarized in the table 9 below.

Table 9: Preliminary Design Parameters

$\varepsilon_{tube}\left(\frac{mW}{kg}\right)$	H_{tube} (cm)	Inner Diameter (cm)	$Q_{plamt}\left(\frac{mL}{s}\right)$
10	1.56	4.23	132.87
20	1.31	4.23	111.73
30	1.18	4.23	100.96

The inner diameter of the tube is kept constant because only one tube will be purchsed and the inner diameter of the tube is largest for the energy dissipation rate of 10. The spacing between the constrictions on the turbulent tube flocculator is four times the inner diameter which is 16.92 cm.

3.3.2 Flocculator Specification

After speaking to Professor Weber-Shirk, the team decided to use one energy dissipation rate of 30 mW/kg. Additional calculations were performed to determine different dimensions of the flocculator. Using $\psi = 75m^{\frac{2}{3}}$ and $\psi = 100m^{\frac{2}{3}}$, the length of the flocculator was calculated from the collision potential ber baffle space and then the number of baffles needed. The following equations were used to find the length of the flocculator (7), residence time(9), diameter of coils(10), number of coils(11), and height of each coil(12).

$$\psi_C = \left(\frac{\Pi_{jet^3}}{2\Pi_{VC}^4}\right) K_b^{\frac{1}{3}} H_{Spacing}^{\frac{2}{3}} = .285m^{.667} \tag{4}$$

$$\psi = \left(\frac{\Pi_{jet^3}}{2\Pi_{VC}^4}\right) K_b^{\frac{1}{3}} = .965 \tag{5}$$

$$N_{Const} = \left(\frac{\psi}{\psi_C}\right) \tag{6}$$

$$L_{Floc} = H_{Spacing\cdot\left(\frac{\psi}{\psi_C}\right)} \tag{7}$$

$$\theta_C = \frac{H_{Spacing}\pi ID_{30}^2}{Q_3^4} \tag{8}$$

$$\theta_{Floc} = \theta_{C\cdot\left(\frac{\psi}{\psi_C}\right)} \tag{9}$$

$$D_{Coil} = \frac{H_{Spacing}N_{ConstPerCoil}}{\pi} \tag{10}$$

$$N_{Coil} = \frac{L_{Floc}}{H_{Spacing}N_{ConstPerCoil}} \tag{11}$$

$$W_{expTube} = \frac{\pi ID_{30} - \pi H_3}{2} + H_3 \tag{12}$$

$$H_{System} = N_{coil} + (H_{tube} + 2T_{Wall} \tag{13}$$

The results of these calculations are shown in the table below 10.

Table 10: Flocculator Parameters

Parameter	$\psi = 75m^{\frac{2}{3}}$	$\psi = 100m^{\frac{2}{3}}$
Number of Constrictions	263.028	350.705
Length of Flocculator	42.265 m	56.353 m
Residence Time	5.659 min	7.546
Diameter of Coil	0.614 m	0.614 m
Number of Coils	21.919	29.255
Unconstricted Height	0.844 m	1.125 m
Constricted Height	1.098	1.464 m

3.3.3 Solenoid Valve Orifice Diameter Calculations

The orifice diameter for a new solenoid valve was calculated. Assuming that pressure of water in the distribution system is approximately 50 psi, the headloss can be determined from equation 14. The orifice diameter of the new solenoid valve was calculated from the derivation shown below.

$$P = \rho g h \tag{14}$$

$$A_{Orifice} = \frac{\pi d^2}{4} \tag{15}$$

$$Q_{Orifice} = \Pi_{VC} \cdot A_{Orifice} \cdot \sqrt{2gh} = \Pi_{VC} \cdot A_{Orifice} \cdot \sqrt{\frac{2P}{\rho}} \tag{16}$$

$$A_{Orifice} = \frac{Q_3}{\Pi_{VC}} \cdot \sqrt{\frac{\rho}{2P}} \tag{17}$$

$$d_{Orifice} = \left(\frac{4Q_3}{\Pi_{VC} \cdot \pi}\right)^{\frac{1}{2}} \cdot \left(\frac{\rho}{2P}\right)^{\frac{1}{4}} \tag{18}$$

The results of the solenoid valve orifice diameter calculations are summarized in the table below.

Table 11: Orifice Diameter Calculations

Headloss	35.153 m
Area	9.378 mm^2
Diameter	3.456 mm

4 Analysis

One of the major problems that this team has had is that this flocculator would require a lot of water. Also, since temperature control is required, heating all that water would require a lot of energy. Recycling the water was considered, but then the entire AguaClara plant would need to be constructed, not just the flocculator.

The team evaluated and considered the hydraulic design of our entire system. Starting with the entrance of the apparatus, we will require a water tank with a temperature control system in order to regulate the temperature of the water. This will be monitored and adjusted using solenoid valves, a temperature probe and Process Controller. Aeration of the tank may be introduced to prevent stratification of the water. It is possible that we will introduce the clay directly into this tank; if this is the case, a 5 gallon bucket may be the solution, since a short-handled mixer is needed to provide turbidity control. Another important component of the stock tank is that it provides a high enough flow rate to satisfy that of our design (approximately 100 mL/s). Using a pressure sensor at the bottom of the tank, the water level in the tank can be regulated by Process Controller. We want the water stock to be fuller if possible, this way the flow rate can be maintained and it will be easier to adjust the temperature.

The transition from the tank to the coagulant dosing is dominated by minor losses. The team believes that using a T-connector from the tank to the flexible tubing will allow any air bubbles trapped in the water to escape to the atmosphere instead of continuing into the flocculator. The point at which the coagulant is dosed into the water will need to experience some period of freefall, which ensures rapid mixing of the coagulant. Angling or slanting the tube with rapid mixing as it travels from the entrance tank to the flocculator will also help prevent bubbles from reaching the flocculator. In the flocculator itself, headloss will be minor loss-dominated as well. The water will travel down to the bottom of the tube flocculator and exit at the top of the flocculator coil. From there, we plan to divert the water to 3 destinations: waste water (to the sink), an imaging system to measure the size of the flocs created by turbulent flocculation, and a sedimentation system to determine how effectively the flocs can be removed. The distance between the point of diversion and the sink ($\mathrm{x_{cm}}$) must be positive, in order for any trapped air to escape out the route for wasted water, as opposed to traveling to the imaging or sedimentation systems. For the sedimentation system we will use a tube setter, followed by a turbidimeter to measure the turbidity of the water after flocs have been settled out. A peristaltic pump after the turbidimeter will regulate the flow being diverted to the sedimentation system. The imaging system will have a similar set up, with the turbidimeter and peristaltic pump placed after a viewing plate from which a camera can capture images of the flocs.

In our design file, we calculated the height of the flocculator ($\mathrm{H_{fl}}$) to be roughly 1.2 meters tall, not including additional spacing to account for our wire duct support structure. As a safety factor, we want to design the actual headloss of the system ($\mathrm{h_{MAX,act}}$) for an energy dissipation rate of 100 mW/kg. The absolute maximum headloss of the system ($\mathrm{h_{MAX,abs}}$) is equal to ($\mathrm{h_{MAX,act}}$) plus an additional 5-10 cm ($\mathrm{y_{cm}}$). Thus, the total height of our system, $\mathrm{H_{total}}$, will be defined as follows: $\mathrm{H_{total}=H_{fl}+x_{cm}+h_{MAX,act}+y_{cm}+H_{ET}}$, where $\mathrm{H_{ET}}$ is the height of the water level in the entrance tank.

5 Future Work

5.1 Building the Flocculator

5.1.1 Additional Materials Needed

The team has only purchased tubing for the flocculator but still has to purchase some materials to build the flocculator including rods for the constrictions, thin-walled, rigid tube to connect the pieces of flexible tube and the wiring ducts to support the coiled tubes.

The team needs to determine the types of bars which will be used to clamp the flexible tubing, creating constrictions along the length of the tube flocculator. The team can measure the force required to compress the flexible tubing, both with and without water, by laying the flexible tubing on top of a rigid pipe. Another rigid pipe will be placed on top of the flexible tubing along with a vessel, which can be filled until the constriction reaches the desired height. The force required for this constriction can be found from the weights of the top rigid pipe, the container and the water. Then, through structural analysis, the force required over the entire bar can be calculated.

The team also has to determine whether the current solenoid valves in the far basement lab will provide enough flow for the apparatus. The flow rate through one of the solenoid valves must be measured. If the flow is significantly less than the design flow rate (approx. 100 mL/s), then solenoid valves with a greater capacity must be acquired.

5.1.2 Construction of Flocculator

Once the team purchases all the materials, construction of the flocculator can begin. The team must also determine where to put the flocculator because it will not be a small apparatus.

5.2 Diverting the Flow

As discussed in section 4, Analysis, the team has to determine where the water should go once it exits the flocculator. The idea was to divert some of the water to tube settlers, some of it for imaging to measure the size of the flocs and the rest to the sink as waste. However, the team has yet to determine how much water should go to each part and has not yet researched specific materials to divert the flow.

5.3 The Rest of the AguaClara Plant

In the future, the rest of the AguaClara Plant could be constructed and recycle could be implemented. Because the turbulent flocculator is the part of the plant that must take up the most space, it is very possible that the rest of the plant could be constructed to fit in one of the AguaClara labs.

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