Turbulent Tube Flocculator

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December 13, 2013

1 Introduction

The purpose of our research is to design, build, and eventually test a lab scale turbulent tube flocculator. This is important because while the AguaClara plants in Honduras and India have flocculation that occurs in turbulent flow, the prior AguaClara program research has focused on laminar tube flocculators. Thus, with the turbulent tube flocculator experimental apparatus, future AguaClara researchers will be able to more accurately conduct research to perfect the design of the full-scale plant. The prior literature that proved most relevant related to either the materials needed for the turbulent tube flocculator to be built or the size of eddies necessary for flocculation.

The 2013 summer semester AguaClara team's design for the turbulent tube flocculator was that the flocculator should be a vertical single coiled tubing configuration. The design used two pairs of pipes to constrict the tube in the coil to create turbulent eddies. The main goal of the Fall 2013 team was to perfect the initial design created in the summer of 2013 and then build the turbulent tube flocculator.

2 Literature Review

Flocculation is a process that transforms a turbid suspension of tiny particles into a turbid suspension of larger particles. A gravity-driven hydraulic flocculator without mechanical agitation is an energy and cost efficient way to achieve flocculation. The flow through a hydraulic flocculator may include turbulent regions, which are caused by the expansion that results when the water changes direction as it flows around each baffle [1]. A fractal description of flocs, estimates of floc separation distances, and estimates of relative velocities of floc particles dependent on the relevant flow regime, provide an overall prediction of the required reaction time for formation of settleable flocs based on influent turbidity, coagulant dose, and energy dissipation rate. Fluid viscosity is important for the beginning of flocculation where colloid sizes are smaller than the smallest fluid eddies. Turbulent eddies are shown to be significant for the final stage of flocculation. In turbulent flow, the collision potential, defined as the product of the hydraulic residence time (θ) and the cube root of the energy dissipation rate (ε), is expected to be a better predictor of flocculator performance than the commonly used product of hydraulic residence time and the velocity gradient $G\theta$. [2].

A high energy dissipation rate is expected to increase collision frequency, creating larger flocs more quickly, but can also break up large flocs in the process. Ideally, the flocs would be less than the maximum (terminal) size reached in the flocculator so that they can grow by capturing other colloidal particles in the water, but not too small as to increase the residual turbidity of the water.

For hydraulic flocculation systems, low turbidity water is produced with minimal fluid shear. Low energy dissipation rates produced the fastest settling flocs and the lowest turbidity water. Because the lowest turbidity water can be produced using large flocs, the flocculator and the sedimentation tank must be designed to not break up large flocs. However, these conclusions have been drawn from laminar flow tube flocculators. While it is likely that the eddies in turbulent flow break up flocs in ways similar to that of laminar fluid shear, this concept has not been tested. Therefore, more research is required to test the performance of adding zones with high energy dissipation rates to break apart and re-form flocs [3].

3 Methods

3.1 Design from Summer 2013 Team

A design for the turbulent tube flocculator was created in Summer 2013. The basic idea for the flocculator is to have a vertical coil of tubes and a series of constrictions created by metal or PVC tubes on the inside and outside of the coil that would be bolted together. Water would flow in from a head tank, flow up through the flocculator and exit to tube settlers, an imaging system or the sink. The following dimensions for the flocculator were estimated:

Parameter	Value
Energy Dissipation Rate	30 mW/kg
Collision Potential	100 $m^{2/3}$
Reynolds Number (Diameter)	4000
Inner Diameter of Tubing	0.0318 m (1.25 in)
Length of Flocculator	56.35 m
Number of Coils	30
Diameter of Coil	0.614 m
Unconstricted Height	1.125 m
Constricted Height	1.464 m
Hydraulic Residence Time	7.546 min

Table 1: Calculated Parameters of Flocculator

3.2 AutoCAD Drawings

To get a clearer idea about the project, the team decided to design the apparatus in AutoCAD. The schematic drawn by the Tube Turbulent Flocculator team in Summer 2013 was taken as the base case and then the first drawing was made - simple and with no specifications.The Fall 2013 team began work to develop the design beyond this first step.

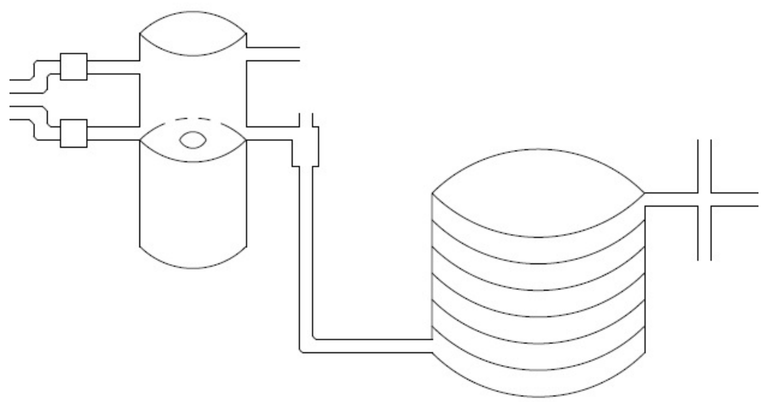

Figure 1: Preliminary Sketch of Apparatus

From the Summer 2013 team's final report, some important dimensions of the flocculator could be calculated: its length and diameter, and the number of coils. Therefore, the following mathematical equations were used to more accurately sketch the system in AutoCAD:

$$D_{coil} = \frac{N_{ConstPerCoil} \cdot H_{Spacing}}{\pi} \tag{1}$$

$$L_{Floc} = H_{Spacing} \cdot \frac{\psi}{\psi_C} \tag{2}$$

$$N_{Coil} = \frac{L_{Floc}}{H_{Spacing} \cdot N_{ConstPerCoil}} \tag{3}$$

The design was redrawn with the correct measurements of the equipment that the team had purchased, such as the diameter of the flexible tubing that makes up the flocculator and a 5 gallon water tank. In addition, the temperature control system which has a sensor and regulates the water temperature by means of solenoid valves and Process Controller was included in the drawing. Another addition was the overflow pipe and pressure control system which regulate the water level inside the tank. The pressure sensor at the bottom bottom of the tank activates the Process Controller which opens the solenoid valve if necessary to regulate the water level. If the system fails and the water level increases, the overflow pipe is responsible for draining the excess to the sink. Finally, a Clay Stock - delivery apparatus was added to the schematic. Stirrers are included to keep the clay stock homogeneous. After adviser's guidance, more details were added, such as the path that the water travels after entering the turbidimeter and the provision for coagulant addition. Coagulant is needed to accomplish aggregation of suspended particles present in solution. Clay particles are in the colloidal (micrometer) size range; their size and negative electrical charge result in stable suspensions in the absence of a coagulant. We intend to use polyaluminum chloride (PACl) as a coagulant. Also since the Hollister Hall B60 lab has a shelf right above the sink, this shelf will be used to hold the coagulant. All turbidimeters were located close to the apparatus so it will be possible to use gravity flow and reduce the number of pumps. The flocculator was moved to near the sink so the space occupied within the lab is now smaller and the outlet is now close to the sink.

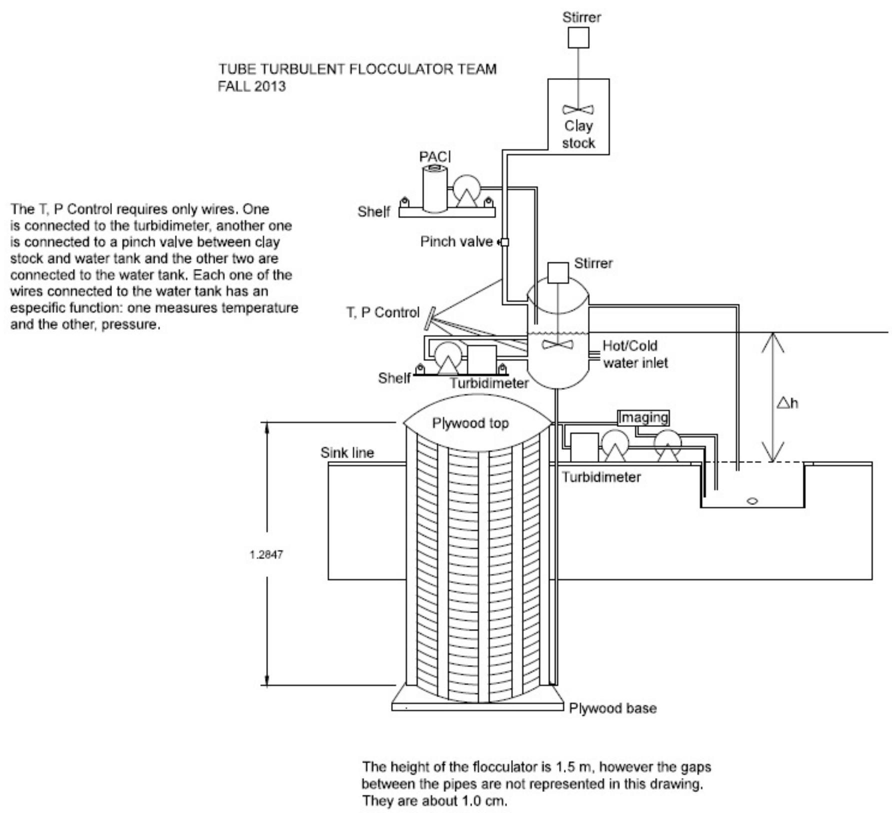

Figure 2: AutoCad Drawing

3.3 Calculations

3.3.1 Head Tank Volume

To ensure accurate influent turbidity, we calculate the minimum head tank volume for our system given the response time of the turbidimeter. A 5 gallon bucket is appropriate.

$$t_{Turbidimeter} = \frac{V_{Sample}}{Q_{Turbidimeter}} = \frac{30mL}{5\frac{mL}{s}} = 6s \tag{4}$$

$$V_{HeadTank} = Q_{Plant}\left(10 \cdot t_{Turbidimeter}\right) = 6.06L = 1.6gal \tag{5}$$

3.3.2 Rapid Mix

We calculate the jet maximum energy dissipation rate for a currently available fitting:

$$\epsilon_{Max} = \frac{\left(\Pi_{Jet} v_{Jet}\right)^3}{D_{Jet}} = 29.6\frac{mW}{kg} \tag{6}$$

The target energy dissipation rate, which ensures uniform distribution of coagulant nanoparticles across colloid surfaces, for rapid mix is 1 W/kg. This level of mixing can be accomplished by passing the flow through a fitting with a reduced inner diameter. We estimated the rapid mix fitting diameter which achieves the target energy dissipation rate with and without vena contracta considerations.

$$D_{Jet} = \left(\frac{4Q_{Plant}\Pi_{Jet}}{\epsilon_{Max}^{\frac{1}{3}}\pi}\right)^{\frac{3}{7}} = 1.45cm \tag{7}$$

$$D_{Orifice} = D_{Jet}\frac{1}{\sqrt{\Pi_{VC}}} = 1.87cm \tag{8}$$

It appears that the 2.4 cm diameter of a currently available fitting does not produce a sufficient energy dissipation rate. If a smaller orifice is built onto the current fitting, it will create an adequate flow contraction. Therefore, the reduced diameter orifice should be designed at 1.87 cm.

3.3.3 Head Loss

The team used notes from CEE 4540 to determine the total head loss in the system. Minor losses from the baffles of the flocculator, major losses from the flocculator, and minor losses from the rapid mix were accounted for. The minor losses from the baffles of the flocculator are given below, where K_B is the baffle loss coefficient and $v_{Flocculator}^2$ is the velocity of water in the flocculator.

$$h_{eFlocculator} = n_{Baffles}K_B\frac{v_{Flocculator}^2}{2g} = 0.554m \tag{9}$$

The major losses from the flocculator, found via the Reynolds number and friction coefficient, are an order of magnitude less than the minor losses. For our system:

$$h_{fFlocculator} = 0.056m \tag{10}$$

The minor losses from rapid mix, which are nearly negligible, are given below, where D_{Jet} is the diameter of the jet, ϵ_{Max} is the maximum energy dissipation rate, and Π_{Jet} is the fractional area of the jet.

$$h_{eRapidMix} = \frac{(D_{Jet}\epsilon_{Max})^{\frac{2}{3}}}{2g\Pi_{Jet}^2} = 0.019m \tag{11}$$

The total head loss in our system is:

$$h_{Total} = h_{eFlocculator} + h_{fFlocculator} + h_{eRapidMix} = 0.629m \tag{12}$$

This 62.9 cm head loss requires a 62.9 cm elevation difference between the water line in the constant head tank and the system outflow, which is easily accommodated in our lab space. The estimated energy loss does not include possible loss caused by coiling of the tubing. This loss will have to be experimentally determined.

3.3.4 Steel Bar in PVC Tube Calculations

To find the maximum size of a square bar to be used to compress the tubing and create flow constrictions, the length of the diagonal of the square was taken to be the same as the inner diameter of the PVC tubing to be used for constriction (to ensure a rounded surface) and, assuming a square geometry, the corresponding width and height were calculated, where a is the width and height of the steel bar and c is the length of the diagonal, or the inner diameter of the tube, which is 0.957 in.

$$a = \sqrt{\frac{c^2}{2}} = 0.677in \tag{13}$$

3.3.5 Compressor Beam Deformation

It was necessary to understand the force of the flocculator tubing (including water) on the compressor beams so that appropriate material can be used.

To estimate the force of the flocculator on the tubes several assumptions and simplifications had to be made. First the force on the beam was estimated from the average force from hydrostatic pressure, (neglecting the force from the moving water) and the force from the elastic tubing. The force was also assumed to be uniformly distributed. The total force was determined to be approximately 114.14 lbf, which makes the distributed force 1.902lbf/in. The deformation type is shown in 3.

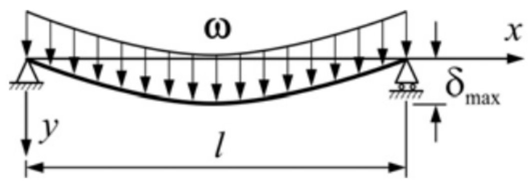

Figure 3: Deformation Type

The moments of inertia for the rectangular and square steel beams were calculated using equation 15. The moments of inertia for the round PVC tubes were calculated from equation 16.

Appropriate material must exhibit less than 1 mm (0.039 in) deflection. The deflection of a beam with a uniform load is given below, where ω is the load density (force/length) from elastic resistance and hydrostatic pressure, l is the length of the beam, $E_{Material}$ is Young's Modulus of the material, and I is moment of inertia. The deformations for the one inch PVC, the rectangular steel bar and the square steel bar were calculated.

$$\Delta x_{Max} = \frac{5}{384} \frac{\omega l^4}{E_{Material} I} \tag{14}$$

$$I_{tube} = \frac{1}{12} bh^3 \tag{15}$$

$$I_{tube} = \frac{\pi}{64} \left(d_{outer}^4 - d_{inner}^4 \right) \tag{16}$$

The following dimensions were used in the calculations:

Name	Height (in)	Width (in)	Moment of Inertia (in^4)	Young's Modulus (psi)	Max Deformation (in)
1.25 in Schedule 80 PVC	1.660 (outer diameter)	1.278 (inner diameter)	0.242	41 x 10^4	3.238
1 in Schedule 80 PVC	1.315 (outer diameter)	0.957 (inner diameter)	0.106	41 x 10^4	7.414
Rectangular Steel Bar	1.25	0.1875	0.031	29 x 10^6	0.036
Square Steel Bar	0.625	0.625	0.013	29 x 10^6	0.871

Table 2: Beam Deformation Dimensions

3.4 Solenoid Valve Testing

The team tested the flow rate of the current solenoid valve that AguaClara had in stock and the hot and cold water flow rate of the sink. The flow rate from the sink had to be measured since, if it did not meet the requirements for the flocculator to work, a direct connection would have to be made with the water pipes.

The solenoid valve was tested by running a tube from the sink faucet, attaching the valve to the end of the tube, and then attaching another tube from the valve to a measuring bucket. The measuring bucket had a capacity of 18L. First, the water was turned on while the valve was off. The valve was turned on and the amount of time that it took for the 18L bucket to fill was measured at 304 seconds.

$$Q = \frac{\Delta V}{\Delta t} \tag{17}$$

The solenoid valve did not provide the required flow rate of the flocculator of 100.96ml/s. Thus, a new solenoid valve with a larger diameter that allows a higher flow rate was purchased.

In order to test the water flow from the sink, the hot and cold water lines had to be tested individually. The experiment was set up by running a tube from the sink to a bucket. Once the sink's hot or cold water line is turned on, we measured the time needed for the bucket to fill to 18L.

Tap	Volume Container	Time	Flow Rate
Cold	18,000 mL	57 sec	315.8 mL/s
Hot	18,000 mL	61 sec	295.1 mL/s

Table 3: Flow Rate of Sink Results

The flow of water to the sink sufficed for both the hot and the cold water flow since both flow rates are greater than the design flow rate of 100.96mL/s. However, since flow will need to switch from hot to cold at least one connection to a water line will be needed.

3.5 Materials for Flocculator

3.5.1 Solenoid Valve

The new solenoid valve required a minimum orifice diameter of 3.456 mm (based on Summer 2013 calculations). The name of the selected Solenoid Valve was RED HAT Solenoid Valve, 2/2, 1/4 In, NC, 120V, Brass (Model Number 6WTP6) from Grainger (Figure 4). The orifice diameter is 5/32 of an inch and the pipe size is 1/4 inch.

Figure 4: Solenoid Valve

3.5.2 Thin Walled Metal Tubing

Name	Size	Price	Model Number
Type M, Hard length, Water	1.25 in x 2 ft	$11.65	4WTL1 (Grainger)

Table 4: Metal Tubing Details

Thin wall tubing was purchased from Grainger with the purpose of connecting the four separate pieces of flexible tubing. The tubing is flexible enough to stretch tightly over the metal tubing as shown in figure 5. The connecting piece of tubing would fit over the other end of the metal tubing. The connection can be reinforced by putting hose clamps around the PVC and metal.

Figure 5: Metal and PVC Tubing

3.5.3 Clamping Materials to Create Constrictions

There are several requirements that the clamping rods need to meet. They must be circular to create smooth constrictions and the pipes used must also have a large enough diameter so that the constrictions are gradual and smooth rather than point constrictions. The team estimated that the inner diameter of the pipes for clamping should be about the same as the flexible tubing for the flocculator, 1.25 inches. In addition, the flexing of the constricting pipes must be minimal so that the constrictions are consistent throughout the flocculator.

The first material tested was 1" schedule 80 PVC - but it has actually a diameter of 1.278 inches. The team determined that these pipes were too flexible to create the constrictions needed and would deform, varying the constriction dimensions along the flocculator. One proposed solution was to reinforce the PVC pipe by adding a rectangular metal pipe through the inside of the PVC so that the metal piece could resist the deformation. The selected steel bar would need to fit inside 1.25" schedule 80 PVC and, in order to make it slide inside the PVC pipe, its diagonal length was calculated to be slightly less than inner diameter of the PVC. The team estimated that there would be negligible deformation with the steel bar in combination with the PVC tubing. The steel bar inside the schedule 80 PVC would need to be set in place with bolts to prevent it from twisting in the PVC.

Based on the beam deformation calculations, the combination of PVC and steel with the lowest deformation is 1 inch PVC with a 1/4 inch x 1 inch steel bar.

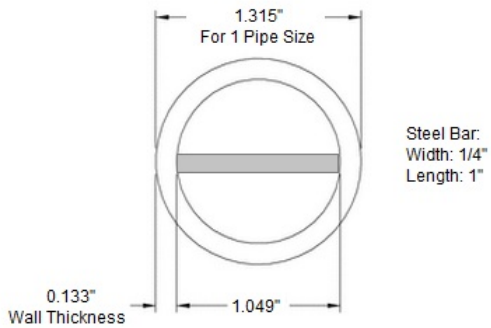

Figure 6: 1 inch Schedule 40 PVC and Steel Bar Insert

3.5.4 Final Materials Purchased

Table 5 give a list of all the materials purchased that were used in the construction of the turbulent tube flocculator.

Product Name	Product Number/Vendor	Specifications	Quantity	Total Price ($)
Standard-Wall White PVC Unthreaded Pipe	48925K93 McMaster-Carr	1 Pipe Size x 5' Length	24	126.48
Low-Carbon Steel Rectangular Bar	8910K383 McMaster-Carr	1/4" Thick, 1" Width	24	458.64
Zinc-Plated Steel Low-Strength Hex Head Cap Screw	91309A560 McMaster-Carr	1/4"-20 Thread, 4-1/2" Length, Fully Threaded	1 (25 per package)	6.03
Bulk Head Fitting	1MKJ2 Grainger	Pipe Size 1 1/4 In	1	16.13
Solenoid Valve	6WTP6 Grainger	2/2, 1/4 In, NC, 120V, Brass	2	166.4
Head Tank Bucket	4269T34 McMaster-Carr	5 Gallons	1	7.83
Machine Screw	1MY62 Grainger	Length: 1-1/2" Thread Size 5-40	1 (100 per package)	12.84

Table 5: Final Materials Purchased

Table 5 is a list of materials that were available in the lab that were also necessary for the construction of the flocculator.

Item Name	Quantity
Paddle Motor	1
Pressure Sensor	1
Temperature Sensor	1
0.25” Bulk Head Fitting	1
Turbidimeter	2
Peristaltic Pump	1
Tubing for Pump	1
Plywood for Base	2

Table 6: Materials for Flocculator from Lab

The motorized paddle mixer is required for continuously stiring the clay in the stock tank. Pressure and temperature sensors are required for the constant head tank. A bulkhead fitting is needed to keep the temperature sensor in the stock tank. Turbidimeters will be needed measure the influent and effluent turbidities. The plywood would be used as a base support structure for flocculator. One piece of plywood will be used on the bottom and the other will be used on top to make the structure more rigid.

3.6 Construction Process

3.6.1 Schematic for Layout of Flocculator

Figure 7 shows how the clamping materials, tubing and plywood base would fit together. The inner PVC will fit inside the holes in the top and bottom plywood. The outer PVC will be slightly shorter so that it can fit in between the pieces of plywood and slide to the desired constriction. There will be bolts to hold the steel in the PVC and the steel bars will end at the top and bottom nails that connect the outer PVC to the inner PVC.

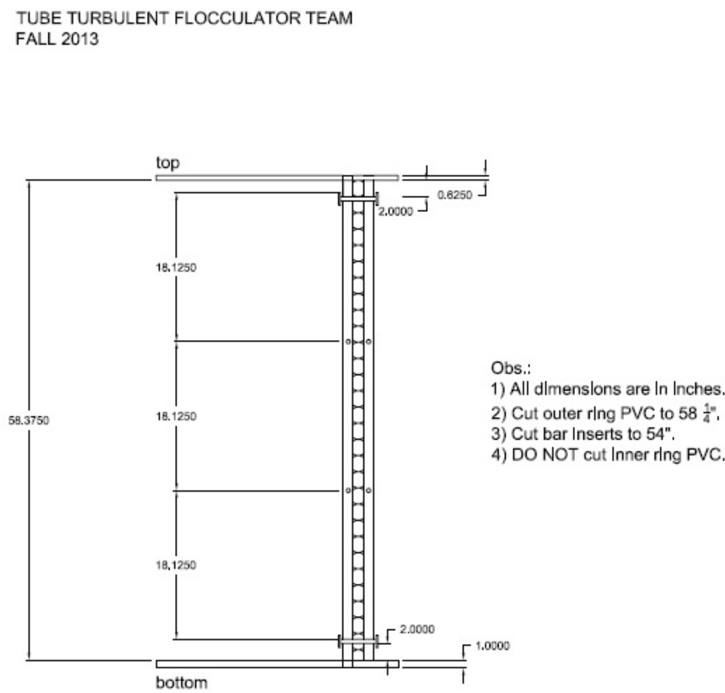

Figure 7: Schematic for Flocculator

3.6.2 Frame for Head tank

A frame was constructed to support the constant head tank, the elevation of which can be adjusted as needed. The frame also allows access for sensor ports around the tank, an outlet at the bottom of the tank, and the option of mounting the clay stock above the head tank. The frame with the bucket is shown in figure 8.

Figure 8: Frame for Constant Head Tank

3.6.3 Drilling Holes in Plywood

Holes for the rigid PVC/steel clamping materials were drilled into two pieces of 1/2" plywood that were glued together to create a 1.0" thick piece of plywood that measures 30" x 30", as shown in figure 9. The holes are for the inner ring of clamping materials and the outer ring will rest on top of the plywood base.

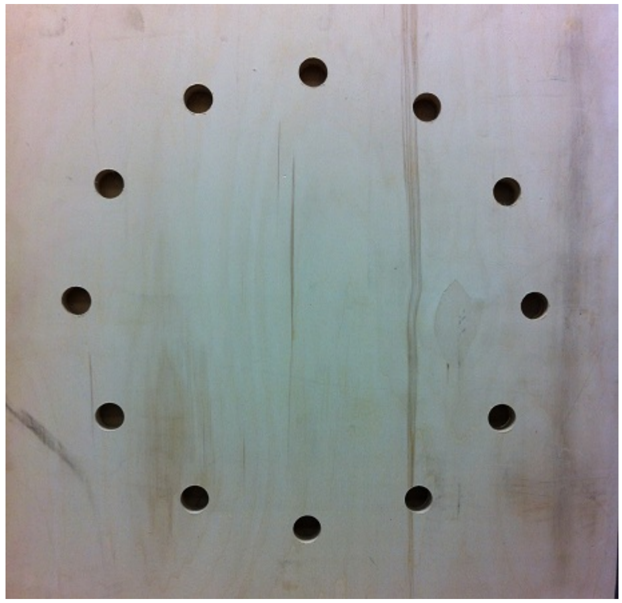

Figure 9: Plywood Base

3.6.4 Supporting Structures

The flocculator must have a stable structure to avoid torsion, tilting, and collapse. The current design uses four 2-by-4 posts anchored to the top and bottom plywood bases to provide stability. A thicker base was also made to anchor the PVC pipes deeper and lower the structure's center of mass. If tipping becomes a problem once the flocculator is in operation, it can be secured to the bench or the wall with a clamp on each axis.

Figure 10: Support Structure

3.6.5 Machining Steel Bars and PVC

Since the steel bars were rough cut, and all approximately 6 feet long, the steel bars had to be cut to 54 inches and the edges of the steel had to be filed down to dull the edges. After the steel bars were cut, two holes were drilled spaced exactly 18.125 inches apart (or 17.9375 inches from each edge.)

The PVC for the outer ring was trimmed so that it could fit between the two wooden boards. Therefore, the half the PVC is 60 inches and the other half is 58.375 inches. Holes in the PVC were drilled to align with the holes in the steel bars. Then the holes for bolting the two PVC tubes together had to be drilled perpendicular to the holes for the bolts to hold the steel bars in place. Since the thickness of the top and bottom pieces of plywood are different, the distance from the bottom of the PVC to the first hole is 3 inches for the inner PVC ring and 2 inches for the outer ring. The distance from the top is 2.625 inches for the inner ring and 2 inches for the outer ring.

3.6.6 Assembly of Flocculator

After drilling all necessary materials, the steel bars were set with pins inside the PVC pipes which were slotted into the plywood frame. Copper piping was used to connect the pieces of flexible tubing (figure 12). The flexible tubing was wrapped around the PVC and the outer ring of PVC was bolted to the inner ring, creating the calculated constriction in the flexible tubing.

The rapid mix unit is a tapered fitting with a piece of PVC on the inside to create the desired orifice diameter to reach a target energy dissipation rate of 1 W/kg. The original diameter of the fitting purchased was 2.4 cm which would yield an energy dissipation rate of 29.642 mW/kg. The diameter was reduced to 1.874 cm. The fitting was inserted just upstream of the flocculator and secured using hose clamps. However, the team has not yet installed a coagulant injection system.

Figure 11: Rapid Mix

Figure 12: Flexible tubing connectors

Figure 13 shows the current flocculator set up. It has not yet been connected to any pumps or turbidimeters.

Figure 13: Current flocculator

4 Future Work

The team is currently testing the main structure of the system. After initial tests with the flocculator, air pockets form because of the constrictions and the geometry of the system. In the future, one of the primary concerns should be researching about how much the air pockets influence the performance of the flocculator and what needs to be done to minimize or eliminate this problem. One possible option could be running tests with higher flow rates to see if the situation is addressed. Another possible solution is to not constrict the tubing until is fully filled with water. Also it would be interesting to check the flexible tubing connectors around the coils to ensure that they do not allow any air to go inside the apparatus. Another problem the team is facing is entirely emptying the flocculator after experiments - one suggestion is using a more potent pump to drain the water to the sink, another possibility is pumping air in one of the ends of the apparatus but this could aggravate the air pockets problem.

Once the team finishes testing the flocculator, all the electronics of the system must be set up so that process controller can read the influent and effluent turbidities, the pressure and temperatures sensors, control the solenoid valves, coagulant dose, and pinch valve. When the controls for the system are put into process controller, the team can run experiments with the entire apparatus ready. Future research is needed to create a video system to image flocs in the effluent and monitor the floc particle size. A system for settling and separation of particles must be designed so that the post-sedimentation effluent turbidity can be monitored and used to evaluate the effectiveness of flocculation.

References

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