Turbulent Tube Flocculator

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May 17, 2014

Abstract

Since the Summer of 2013, the Turbulent Tube Flocculator team has been developing and optimizing a design for a lab scale turbulent tube flocculator to better mimic the processes that occur at full scale plants. From this, a vertical flocculator of approximately 1.5 m was constructed with 30 coils of flexible tubings connected with pieces of metal pipe. Currently, the team is working on the rest of the experimental setup, which involves pumps, turbidimeters, pinch valves, clay stock, temperature and pressure sensors, Settled Water Turbidity analyzer (SWaT), rapid mix, and Process Controller software. Clay will be added directly to the head tank to keep the suspension stable in absence of coagulant. The coagulant, injected immediately following rapid mix, is responsible for aggregation of suspended particles present in the solution. Experiments will measure turbidity reduction as a function of coagulant dosage.

1 Introduction

The purpose of our research is to design, build, and test a lab scale turbulent tube flocculator. This is important because while the AguaClara plants in Honduras and India have turbulent flow flocculators, previous AguaClara research has only formed hypotheses from laminar flow 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 to this project related to either the materials needed for the building of the turbulent tube flocculator or to the size of eddies necessary for flocculation.

The 2013 Summer AguaClara team's design for the turbulent tube flocculator was a vertically-oriented, large coiled tube. The design used twelve pairs of pipes to constrict the tube 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 and executed in Fall 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 a settled water turbidity unit, an imaging system and the sink. The following dimensions for the flocculator were estimated (see table 1).

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 Assembly Process

3.2.1 Assembly of Flocculator

After machining 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 1). The flexible tubing was wrapped around the PVC and the outer ring of PVC was bolted to the inner ring, creating the calculated constrictions in the flexible tubing. The final flocculator is shown below (figure 2). After initial tests, the team faced an issue: the formation of air bubbles inside the flexible tubing (figure 3). Some kinks were maximizing the problem, so zip ties were applied to reduce the severity of the additional constrictions.

Figure 1: Flexible Tubing Connectors

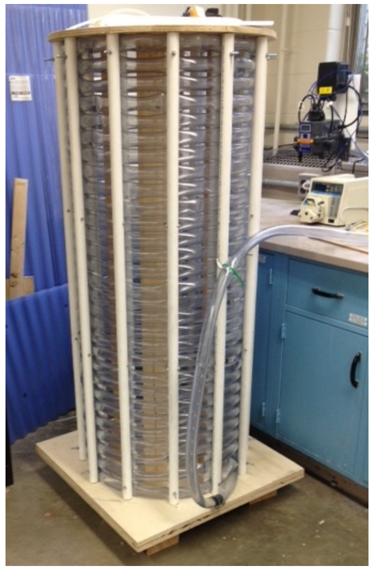

Figure 2: Current Flocculator

Figure 3: Air bubbles issue

3.2.2 Clay Stock Tank and Constant Head Tank

A frame supporting the clay stock tank and constant head tank has been assembled. Turbidity will be monitored in the head tank, and commensurate flow from the clay stock to the head tank will be controlled with a pinch valve. Temperature will also be monitored in the head tank, and commensurate flow of hot or cold water will be controlled with two solenoid valves. Finally, pressure will be monitored in the head tank to maintain the hydraulic grade line.

The setup is shown in figure 4. The tank on the top is the clay stock tank and the one underneath is the constant head tank. The blue boxes on the side are the solenoid valves, which are connected to the constant head tank.

Figure 4: Clay Stock Tank and Constant Head Tank

The required flow rate through the system is 100 mL/s, which can be adjusted by changing the height of the bucket and the height of the waste tube. The flow rate through the system was measured to be about 90 mL/s (by filling a graduated cylinder with water from the waste line over a certain amount of time and adding the SWaT flow rate of 1.00 mL/s. Therefore, the team raised the height of the constant head tank by putting a wooden board under the stand and then raising the stirrers and bucket, and lowering the waste line. The new flow rate through the system is approximately 100 mL/s.

3.2.3 Rapid Mix and Drain Pump Module

After discussion, the team chose to change the rapid mix design, with a new module to house it and a pump connection to be used for draining. The rapid mix will be a small orifice with diameter 0.783 inches, which is set in the module to achieve a target energy dissipation rate of 1 W/kg. Coagulant will be dosed immediately following rapid mix via a needle interface built into the module. The pump connection will allow for the attachment of a centrifugal pump for draining the entire system when necessary. The design and completed module are shown in figures 5 and 6.

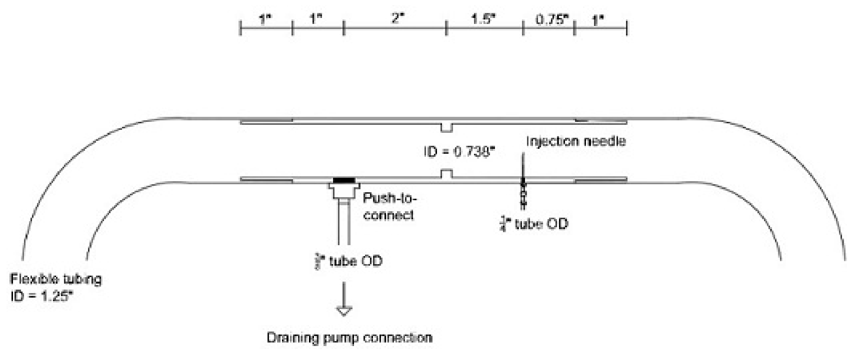

Figure 5: Rapid Mix Design and Drain Pump Position

Figure 6: Rapid Mix and Drain Module

3.3 Settled Water Turbidity Analyzer (SWaT)

3.3.1 SWaT Calculations

Based on the AguaClara approach for plate settler design, the minimum spacing to prevent floc rollup is 2.5 cm (or 0.984 in), so the minimum diameter for the tube is 1 inch [4]. With a target capture velocity, the length of the tube settler could be determined from equation 1, where S is the spacing or the diameter of the tube, L is the length of the tube, V_{Plate} is the vertical velocity going through the tank and alpha is the plate angle (set at 60 degrees) to get solids to slide down the incline. We found that a length of 86 cm is required for the tube settler.

$$V_{Capture} = \frac{S \cdot V_{Plate}}{L \cdot sin(\alpha) \cdot cos(\alpha) + S} \tag{1}$$

Equation 2 was used to determine the flow rate. The minimum flow rate through the turbidimeter is 100 mL/min to prevent particles from settling in it. With a length of 86 cm, the flow rate through the tube settler will be 100 mL/min.

$$Q_{Tube} = A_{Tube} \cdot \frac{V_{Capture} \cdot (L_{Tube} sin(\alpha) \cdot cos(\alpha) + D_{Tube}}{D_{Tube}} \tag{2}$$

A diagram showing the geometry of the tube settler with the appropriate labeled dimensions is shown in figure 7.

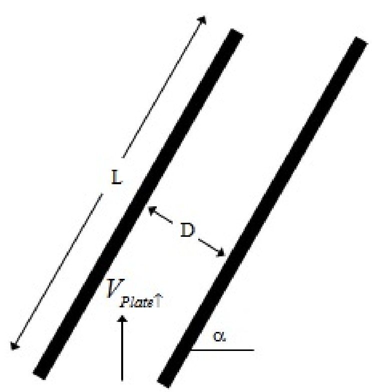

Figure 7: Tube Settler Geometry

3.3.2 Design

Based on the calculations, the settled water turbidity unit has been designed and fabricated to measure effluent turbidity. The SWaT system is located immediately following the flocculator and consists of a tube settler, turbidimeter and peristaltic pump. The specifications for the tube settler are given in the table 2 below. A diagram of the SWaT system is shown in figure 8.

Parameter	Value
Length	86 cm
Inner Diameter	1.049 in
Angle	60 degrees
Capture Velocity	0.174 mm/s
Flow Rate	100.7 mL/min

Table 2: Calculated Parameters of Tube Settler

Figure 8: SWaT Apparatus

3.4 Process Controller

Process controller monitors and regulates the water level, temperature and turbidity in the constant head tank. The turbidity is measured by a turbidimeter loop, and the "on/off" controller vi (visual instrument) tells the clay pinch valve when to add more clay. States control the water level and the temperature. There are three states in total: off, filling, full, add hot water and add cold water. In the off state, everything is turned off. Filling adds both hot and cold water until the water level reaches a set minimum. The hot and cold water states add water of the appropriate temperature if the water level is too low. Figure 9 shows when process controller transitions between different states.

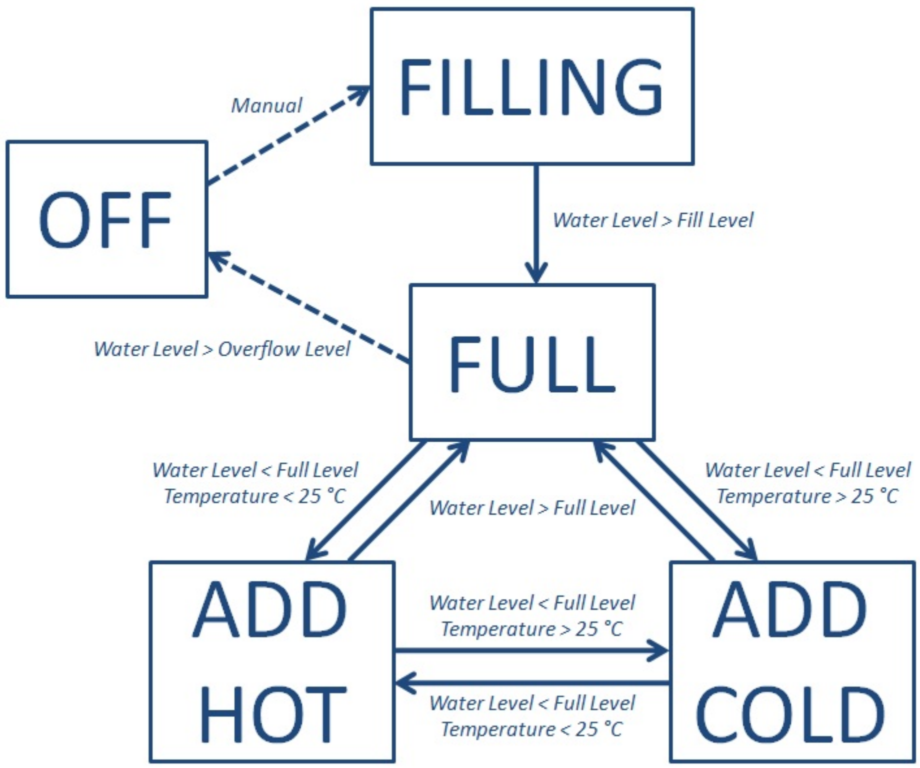

Figure 9: Process Controller Logic Map

3.5 Cleaning the Flocculator

The team has also been working on methods to clean out flocs that settle out in the flocculator. So far the team has tried simply flushing the system with a high flow, and then pumping all the water out of the system so that hopefully the flocs will get pulled out along with the water. However, this has only been mildly successful.

Other flocculation teams have run small pieces of sponge through the flocculator to remove the coagulant and clay that have adhered to the walls of the flocculator, but with the current apparatus the sponge would have too many opportunities to get stuck along the way, particularly through the rapid mix unit, and through each constriction in the flocculator.

4 Analysis

4.1 Experiments

The team performed a few tests with a target influent turidity of 50 NTU and a coagulant dose of 10 mg/L. The concentration of clay in the clay stock tank is 10 g/L (10 grams of clay to 1 liter of water) and the concentration of the coagulant stock is 5 g/L. Though this is a much higher coagulant stock concentration than what other teams have used in the past, the flow rate of the turbulent tube flocculator is also much higher than what other teams have had. To make this concentration, the team uses concentrated liquid PACl and dilutes it to the appropriate concentration using distilled water. The current lab stock concentration is 62.02 g/L so the volume of coagulant needed can be calculated in equation 3, where C_{Stock} is the desired stock concentration of 5 g/L and V_{Stock} is the volume of the container holding the stock concentration. The volume of PACl needed is 0.242 L. Therefore, 2.758 L of distilled water is required to make the coagulant stock.

$$V_{LabStock} = \frac{C_{Stock} V_{Stock}}{C_{LabStock}} \tag{3}$$

Because there is no floc blanket formation in this system, the main factor determining the length of experimentation is the hydraulic residence time which is 7.55 minutes.

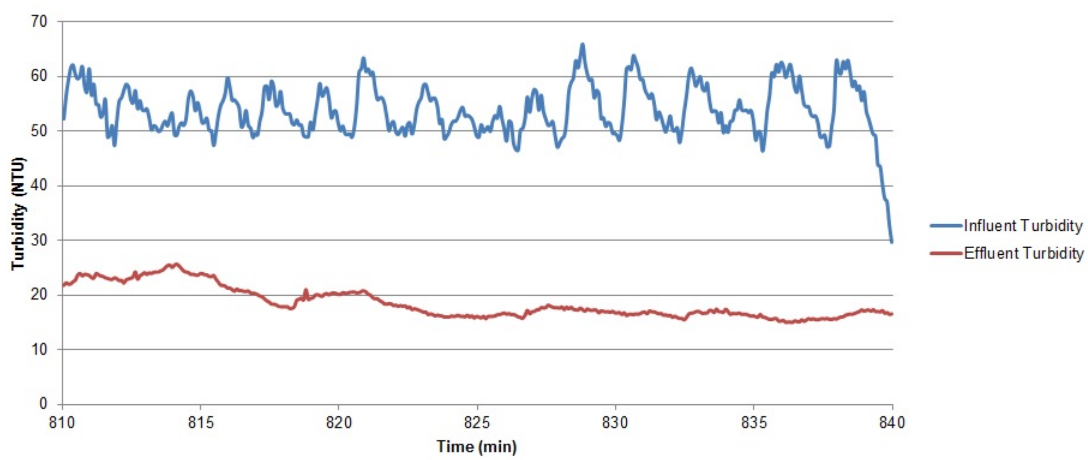

Figure 10: Graph of Influent and Effluent Turbidity

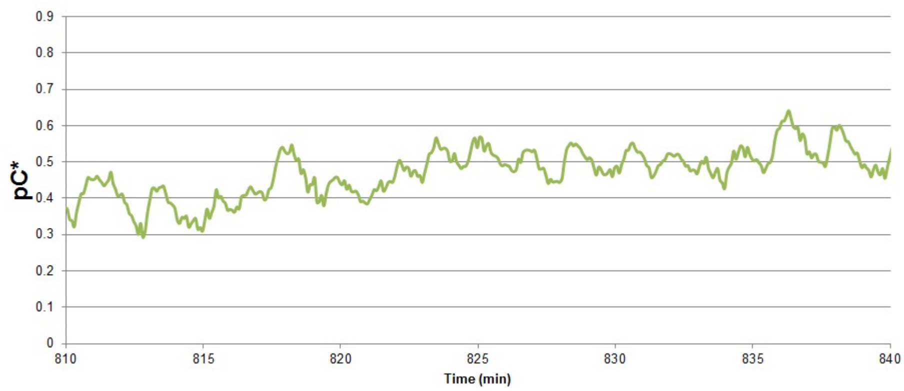

Figure 11: Graph of pC*

Figure 10 shows the influent and effluent turbidities and figure 11 is a graph of pC* (defined in equation 4).

$$pC* = -log(\frac{Effluent(t+\theta)}{Influent(t)}) \quad (4)$$

Based on the results from preliminary experiments, there are a number of problems and potential modifications that should be addressed in order to improve the performance of the flocculator. First, the influent turbidity should be held constant at 50 NTU, but it fluctuates between 50 and 60 NTU. The team predicts that this is because of the long response time between the influent turbidimeter, process controller and the clay pinch valve.

The effluent turbidity for this experiment was also very large (and pC* was very low), which could be due to a problem with the coagulant dosing system so that the experiment was essentially running 50-60 NTU water through the flocculator without any coagulant. This is probably because the needle (steel tubing with inner diameter of 0.394 mm) that was being used to inject coagulant became clogged, probably from solids forming at the tip of the needle.

4.2 Air Bubbles

To remove as many air bubbles from the system as possible before running the experiment, the team has been folding over the end of the waste line to prevent any water from flowing through it, while simultaneously releasing the air release (figure 12) right after the tube settler to allow the system to fill with was much water as possible instead of air. As figure 12 shows, the part of the tubing where the air release is, is rigid and the tubing before and after it is flexible. When air is released from the system in this way, it creates a vacuum in the tubing right before and after the release which creates unintentional constrictions in the tubing. This may be unimportant since this part of the apparatus is located after SWaT, so all of that water is going to waste anyways. However, the danger of it is that it creates additional constrictions between the end of the flocculator and the beginning of SWaT, which would increase fluid velocities in the final coils of the flocculator that could break apart flocs.

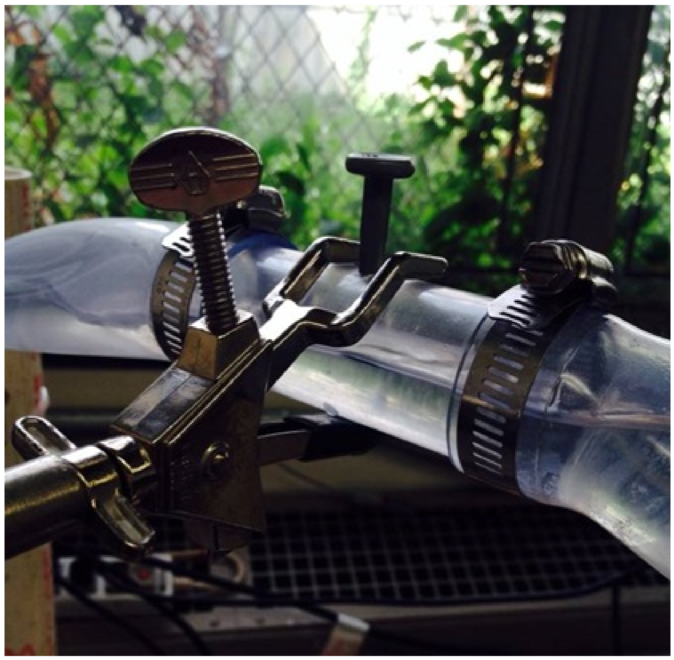

Figure 12: Air Release

5 Conclusions

The team will have to run a number of additional experiments in order to draw any conclusions about floc breakup theory with the turbulent tube flocculator. There are still a number of issues with the flocculator that will have to be addressed before the flocculator will yield a desirable effluent turbidity and pC*.

6 Future Work

6.1 Head Tank Restructuring

The team currently uses an air release plug at the end of the flocculator to release air from the system as described in Section 4.2. The constrictions this pressurization creates in the tubing are likely having a significant impact on floc stability, creating high fluid velocities that shear the flocs we have created. We have decided to leave the air pocket at that location, but the head tank must be raised to maintain a flow rate of 100 mL/s. We have already switched the clay stock tank and the constant head tank. This means that clay stock will now need to be pumped up to the head tank with a peristaltic pump. To achieve constant influent turbidity, the team should set up the clay pump to use a "PID" .vi file in process controller that changes the pump speed proportional to the deviation from target turbidity.

6.2 Coagulant Injection Replacement

The needle that was injecting coagulant immediately following the rapid mix orifice was clogging and preventing coagulant from being added to our raw water. For the moment, it has simply been replaced with 1/4" tubing, however this does not inject the coagulant at the center of the rapid mix jet (at the centroid of the tube). A new injection device should be installed using thin tubing fed through a push-to-connect plug. This change should dramatically improve particle aggregation and dramatically decrease effluent turbidity.

6.3 New Air Release Chamber

To solve the issue of air bubbles exiting the flocculator and entering SWaT, which disrupts effluent turbidity measurements, a new air release chamber should be installed in between the flocculator and SWaT. The rigid tubing from the current air release could be repurposed for this system (Tim in the shop helped us turn down the inner diameter of the PVC tee so that the non-standard rigid tubing would fit snugly inside the fittings). It should mimic SWaT, in that a vertical 1" PVC pipe (which does not need to be nearly as long as the SWaT tube settler) will divert some flow into a chamber which can be opened and closed (with a plug or a valve). This way, air bubbles that are pushed out of the flocculator will rise into this chamber and can be periodically released, rather than passing on into SWaT.

6.4 Experimentation

The next goal is to start running tests to measure the effluent turbidity to evaluate the overall effectiveness of the flocculator. A major problem that the team has to address is that the stamp box experiences unexpected failures, of which the cause remains unknown. In the long run, tests will be performed to determine if there is a correlation between the amount of air gaps and the effectiveness of the turbulent flocculator. If there is, the team will have to find possible solutions to the issue.

The team is also working on the best way to clean the flocculator since an unexpected amount of clay is settling out in the flexible tubing between the head tank and the rapid mix. Further tests will be performed to determine other viable options for cleaning the flocculator.

Once these problems are addressed, the team will begin to compare the effluent and influent turbidities and how they are affected by coagulant levels. Eventually, the team will also run experiments at varying coagulant doses and test floc break-up theory.

References

[1] Weber-Shirk, Monroe. Flocculation Model. N.d. PowerPoint notes from CEE 4540. Https://confluence.cornell.edu/display/cee4540/Syllabus.

[2] Monroe L. Weber-Shirk, Leonard W. Lion, Flocculation model and collision potential for reactors with flows characterized by high Peclet numbers, Water Research, Volume 44, Issue 18, October 2010, Pages 5180-5187, ISSN 0043-1354, http://dx.doi.org/10.1016/j.watres.2010.06.026. (http://www.sciencedirect.com/science/article/pii/S0043135410004136)

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