Turbulent Tube Flocculation

Shreya Jain, Tanya Peifer, Nadia Shebaro, and Luke Zhu

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Abstract

Over the summer of 2014, the turbulent tube flocculation team has worked to implement and test a SWaT system for analyzing residual turbidity from the flocculator. The group is also working to implement PID control for the turbulent tube flocculator to regulate the amount of clay added to the system. The team made minor physical adjustments to the turbulent flocculator through the shortening of tubes and the tube settler position. By the end of the summer research period, the team has established a working flocculation system to facilitate experiments done by future teams.

Literature Review

In the flocculation process, colloids and flocs collide with other colloids and flocs to form larger flocs. Because these larger flocs settle out more quickly, they can more easily be removed from the water when in the settling tank. However, it has been suggested that when flocs become large enough, colloids are less likely to attach to them due to the increased surface shear. Once a floc reaches its maximum size, colloids and flocs no longer interact in the same way and the colloid/floc collisions are likely no longer effective. Therefore, it has previously been proposed that large flocs are not useful and that better performance might be accomplished by breaking large flocs apart so that additional colloids may attach to the smaller flocs[1].

In turbulent tube flocculators, a good measure of the amount of flocculation that will occur is given by the collision potential:

$$\psi = \theta \times \varepsilon^{\frac{1}{3}} \tag{1}$$

where θ and ε represent the hydraulic residence time and energy dissipation rate respectively.

The rate of flocculation is dependent on the energy dissipation rate throughout the flocculator. A higher energy dissipation rate corresponds to a higher velocity gradient as can be seen in equation (1). This higher velocity gradient implies that there will be a greater number of collisions in the flocculator. A higher energy dissipation rate also leads to more floc break-up. This break-up has the potential to be both beneficial and detrimental to the process. On one hand, floc break-up may cause there to be fewer settleable flocs. However, as was previously stated, it appears to be difficult for colloids to attach to large flocs, and floc break-up may therefore allow for additional flocculation.

The performance of a flocculator is measured by its residual turbidity after the colloids and flocs have aggregated and settled. An equation for residual turbidity has been proposed by Swetland, et al. [?] and is shown below:

$$pC* = \frac{9log(e)}{8} W(\frac{8}{9}\Gamma\phi_0^{8/9}\frac{t\varepsilon^{\frac{1}{3}}}{d_{Colloid}^{\frac{2}{3}}}\frac{\eta_{Coag}}{V_{Capture}}) \tag{2}$$

where $pC*$ is the negative log of the residual turbidity divided by the influent turbidity, W is the Lambert W Function, Γ is the fractional coverage of colloids by coagulant,ϕ_0 is the initial floc volume fraction,t is the flocculation time, ε is the energy dissipation rate, $d_{Colloid}$is the characteristic colloid size, η_{Coag} is the characteristic sedimentation velocity of the floc suspension, and $V_{Capture}$is the sedimentation tank capture velocity.

Most flocculators in AguaClara plants experience turbulent flow as opposed to laminar. Therefore, it is important to test the theories from laminar tube flocculation in turbulent conditions.

Introduction

Apparatus

A schematic of the turubulent apparatus is given below in Figure 1.

a) The clay stock had a concentration of 10 g/L and was continuously mixed to prevent the clay from settling in the stock tank. The clay was pumped into the head tank by a peristaltic pump. This pump was controlled by PID, and the rate at which the clay was added was determined by the instantaneous state of the turbidity in the head tank. The PID system was designed to keep the raw water in the head tank at a relatively constant turbidity.

b) The raw water was stored in an elevated head tank. Temperature and pressure sensors were implemented in this tank so that the water level and water temperature could be controlled. Two influent tubes brought tap water directly into the tank, one from a warm water faucet and one from a cool water faucet. The influent from each tube was controlled by separate solenoid valves. An overflow line was also situated near the top of the tank that drew water from the tank into the sink so that the water level in the tank would not pass a certain height.

c) The turbidity of the water in the head tank was obtained by pumping the water in a loop through a turbidimeter. The reading from this turbidimeter gave the influent turbidity and was used to control the PID system that dictated the addition of clay to the head tank.

d) Water from the head tank flowed directly down into the flocculator through large flexible PVC tubing with an inner diameter of 31.75 mm (1.25

inches). The tank was set up such that the influent to the turbidimeter had a flow rate of approximately 100 mL/s.

e) Polyaluminum Chloride (PACl) was dosed to the influent water using a peristaltic pump. The PACl dosage was injected into the larger influent tube, and the water immediately passed through a rapid mix chamber before entering the flocculator.

f) Turbid water flowed entered through the bottom of the flocculator, up through the tubing, around the flocculator in a concentric spiral, and exited at the top. Throughout the flocculator, there were compressions in the flexible tubing in order to create zones of higher energy dissipation.

g) After exiting the flocculator, a portion of the water was pumped up through the tube settler using a peristaltic pump, and the remainder was simply drained from the system. The tube settler was an 86 cm long PVC tube, which was situated at an angle of 60^o in order to facilitate settling without allowing for floc roll-up. In order to achieve a capture velocity of 0.12 mm/s, the flow rate through the tube settler wa approximately 70 mL/min.

h) After passing through the tube settler, the effluent water was passed through another turbidimeter in order to determine the effluent turbidity. The peristaltic pump placed after this turbidimeter control led the flow through the tube settler. The water from the effluent turbidimeter then drained into the sink.

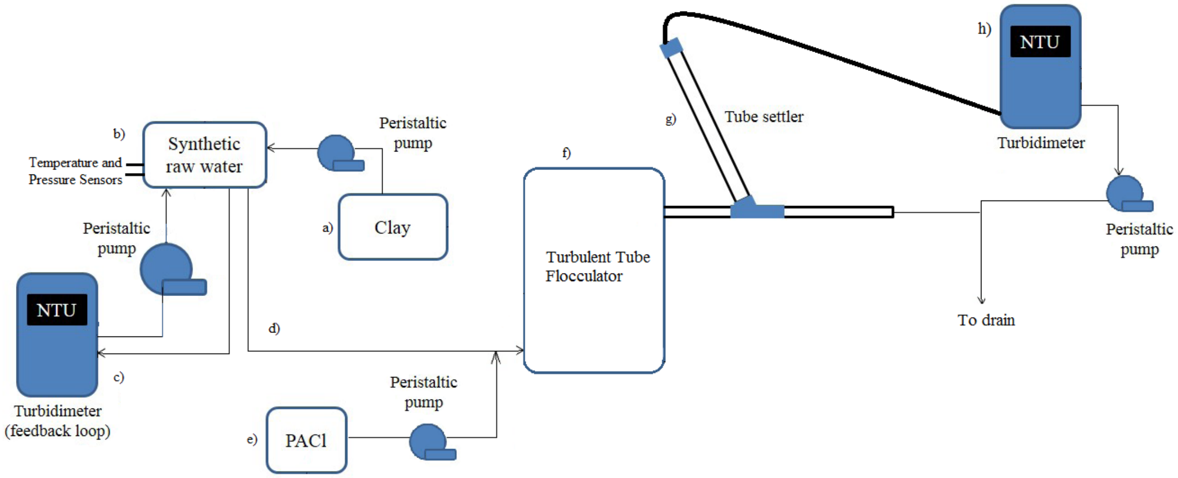

Figure 1: Turbulent Tube Flocculator Schematic

Method File

The method file for the turbulent flocculator was set up to control the temperature of the water in the head tank. This was achieved by using five states, listed below, which controlled whether hot or cold water was added to the tank. The goal was to maintain the water in the head tank at a temperature that was roughly equal to the ambient temperature and at a relatively constant and high water level without overflowing. The system of routinely adding hot or cold waterwas designed to maintain a water height that was right around the height of the overflow drain at all times. This system included two thermistors, one measuring the water temperature and one measuring the ambient temperature, and one pressure sensor measuring the height of water in the head tank. The influent into the tank consisted of two tubes flowing from hot and cold water faucets, each of which was controlled by a solenoid valve. The states are shown in Figure 2 and were as follows:

1) Off: In this state, all valves and pumps were off. Nothing was flowing through the system.

2) Filling: In this state, both the hot and cold water solenoid valves were open, and water flowed into the head tank in order to fill it up before the flocculator was run. Once the water level reached a baseline level, the system transitioned to either the Add Hot Water or the Add Cold Water state, depending on the instantaneous water temperature in the bucket.

3) Full: This was the state entered when the head tank was filled with water and the temperature of the water was approximately equal to the ambient temperature. In this state, both the hot and cold water solenoid valves were turned off. This was also the state in which the turbulent flocculator apparatus began to be run. In this state, the clay pump turned on and began dosing clay by PID control. The coagulant pump also turned on and dosed PACl with a flow rate given by Process Controller. Additionally, the tube settler pump turned on and began pulling water up through the tube settler in order to run SWaT.

4) Add Hot Water: This state was mostly identical to the full state, in that the flocculator system was running, except that the solenoid valve for the hot water tube was open in order to allow hot water to flow into the head tank. The system entered this state when the water level was below the full level and the water temperature was below the ambient temperature.

5) Add Cold Water: This state was also mostly identical to the full state, except the solenoid valve for the cold water tube was open in order to allow cold water to flow into the head tank. The system entered this state when the water level was below the full level and the water temperature was below the ambient temperature.

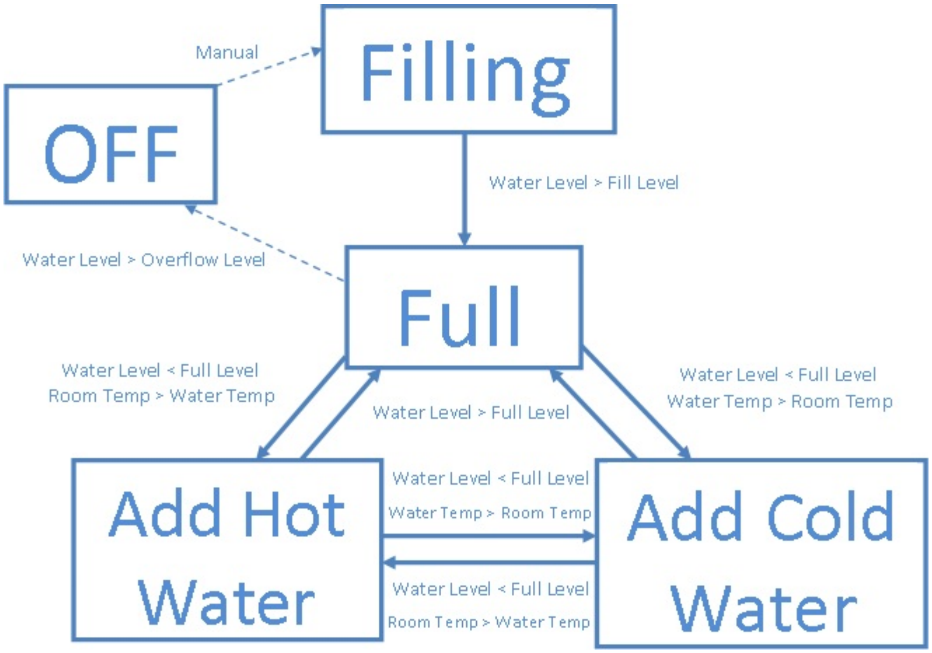

Figure 2: Schematic of Temperature Control Process

Methods

Fabrication

System Modifications

Several modifications were made to the flocculator in order to prepare it for experimentation. First, the tube settler was set up such that it was at an angle of 60^o in order to achieve good settling. Two ring stands were used to hold up the tube settler, and it was stabilized in a position that held it up at an angle of 60^o. When the settler was run, it was also observed that there was a lot of turbulence at the bottom of the tube. In order to attempt to reduce the possible interference with settling, the final compression in the flexible tubing leading to the tube settler was removed. However, the tubing was still slightly bent due to being in a compressed position for so long, and it still needed to be supported in order to remain straight.

The flocculator also experienced problems with air entering the system. When the head tank and the flocculator were allowed to drain, air entered the system which interfered with flocculation and settling din subsequent runs. In order to release air, the small air hole in the tubing after the SWaT was opened and elevated. However, the best solution proved to be to not let air enter the system when it was turned off. If the drain tube was properly elevated, the water level in the influent and effluent tubes would remain sufficiently high to prevent air from entering the system, which eliminated the problem of having to remove all of the air at the beginning of an experiment.

The turbulent tube flocculator required a flow rate of 100 mL/s. Initially, the flow rate was too high at around 170 mL/s. This issue was resolved by reducing the difference between the level of water in the bucket and the level of the air-water interface in the drain tube at the end of the flocculator. Using trial and error, the exit tube was incrementally raised until the desired flow rate of 100 mL/s was achieved.

Finally, the team wished to investigate the head loss through the flocculator body. This was achieved through the introduction of a second 7 kPa pressure sensor that connected the top of the flocculator with the bottom of the flocculator. A 6.35 mm (1/4 inch) hole was drilled into the hard PVC tubing near the tube settler, where one end of the pressure sensor was attached. The other end was inserted into a 6.35 mm (1/4 inch) opening in the hard PVC immediately before the flocculator, which had previously been used as an air outlet at the bottom of the flocculator.

Flow Rate Monitoring

The flow rate of water draining into the flocculator from the head tank, and thus the flow rate through the flocculator, was determined by filling the bucket with water, subsequently allowing it to drain, and monitoring the change in height of the water over time. A pressure sensor monitored the height of the water in the bucket as it drained. After the bucket filled with enough water so that excess water was drained from the top, roughly 30 cm above the bottom of the bucket, influent water was shut off, and the bucket was left to drain. The rate of change of the water level was equivalent to the velocity of flow through the bucket, which is proportional to the flow rate based on the area of the flow. The flow rate is given by$Q = \Delta h \pi r^2$, where r is the radius of the bucket and h is the height of the water.

It was initially expected that the flow rate out of the bucket would decrease linearly with the decreasing water level; however, the data that was observed did not clearly indicate this. The flow rate through the bucket initially appeared to be constant, as the change in height was linear with time for the entire drainage period. However, it is likely that this is a result of the tapering of the bucket, which caused the area of the flow to decrease as the bucket drained. The effects of this tapering could also be observed when the bucket was being filled, as the height of water increased more quickly when the bucket was less full. Therefore, it is likely the case that the flow rate was in fact decreasing as the bucket emptied, but the downward velocity of the water level in the bucket remained relatively constant.

The system was adjusted to achieve the appropriate flow rate of 100 mL/s when the bucket was flowing fully, at which point the water level was maintained fairly steady at the height of the overflow drain outlet. The area that was used to calculate the flow rate was determined based on the radius at the top of the bucket, as this was equivalent to the radius of the bucket at the height of the overflow drain. Therefore, the system was set up such that the water flowed through the flocculator at a rate of 100 mL/s when the water level was at the height of the overflow drain, but would not acheive this same target flow rate when the water level was at a different height.

Energy Dissipation Rate

After inserting a pressure sensor to monitor the head loss through the system and achieving the target flow rate through the flocculator of 100 mL/s, the team attempted to determine the average energy dissipation rate through the flocculator.

Based on the work of previous teams, it appeared as though the system was designed in order to achieve a maximum energy dissipation rate through the constrictions of 25-30 mW/kg.

The average energy dissipation rate actually observed through the system was calculated based on the equation $\varepsilon = gh\theta$, where ε is energy dissipation (mW/kg), g is the gravitational constant (9.81 m/s^2), h is the head loss (m), and θ is the residence time. The head loss observed when running the system at 100 mL/s was approximately 65 cm. The residence time at this flow rate was approximately 7.5 minutes. This gave an average energy dissipation rate of approximately 14.1 mW/kg through the entire flocculator.

Clay PID Control

In order to run longer experiments on the system, the team designed a method of using PID control to maintain a relatively constant influent turbidity.

The first step that was taken towards this end was to determine the maximum concentration of clay stock that can be sent through a peristaltic pump. Because the goal was to run relatively long experiments with high turbidity water (up to 500 NTU) and a high flow rate (100 mL/s), it was important to use as high of a stock concentration as possible in order to reduce the frequency with which the bucket needed to be refilled. The team tested stock concentrations as high as 75 g/L of clay and did not observe any problems with the ability of the peristaltic pump to feed the clay stock into the tank.

Having determined a reasonable stock concentration, the next step was to physically set up and implement a PID system that was able to respond quickly and sensitively enough to maintain the influent turbidity within an appropriate range during experiments. The setup of the system made it somewhat difficult to implement PID because the water would drain out of the head tank through the large 12.7 mm (1/2 inch) tubing and went directly into the flocculator. The clay was pumped from the stock tank into the head tank, and the influent turbiditimeter circulated water from the head tank in order to monitor the turbidity that was being maintained in that bucket. A little bit of experimentation was done to determine if it would be at all feasible to implement PID while still maintaining the same general setup was in place. However, it was difficult to tell whether or not this system would be able to respond efficiently enough to maintain an appropriate effluent turbidity at all times during experimentation. Trial and error will have to be done with different P and I values in order to determine if the system will be able to avoid large spikes or errors that cause inappropriate influent turbidities or fluctuations to occur at any time during experimentation.

Testing PID, Temperature, and Height Control

The system was designed to maintain a constant influent turbidity by means of PID, to keep the water temperature roughly equivalent to the room temperature, and to keep the height of water in the head tank relatively constant so as to maintain the appropriate flow rate at all times. Some initial testing was done to determine how effectively the methods described above were able to maintain these values at appropriate levels. Figures 3, 4, and 5 show the results of running the system for a period of over 2.5 hours and monitoring the relevant parameters.

These systems appear to have worked effectively for long periods, but it is clear that there are occasional large fluctuations that would not be acceptable during an actual experiment. It is notable that all three of the parameters appeared to experience spikes at the same time, which indicates that there may be a common underlying cause to these errors. The most notable spike was observed after approximately 5800 seconds of running. Here, the PID fluctuated very widely, the height of water in the bucket increased noticeably, and the temperature of the water underwent a very significant decrease. All three of the parameters were interlinked, but it is difficult to determine exactly which one was responsible for triggering the error. One possibility is that something occured with one of the solenoid valves, causing the temperature of the water to decrease significantly.If the cold solenoid valve were running for too long, this could also have caused the height of the water to increase. It is likely that this change in water level caused the turbidity in the tank to decrease, because the overall volume of the turbid water was increased, which then caused the PID system to respond with a very large fluctuation.

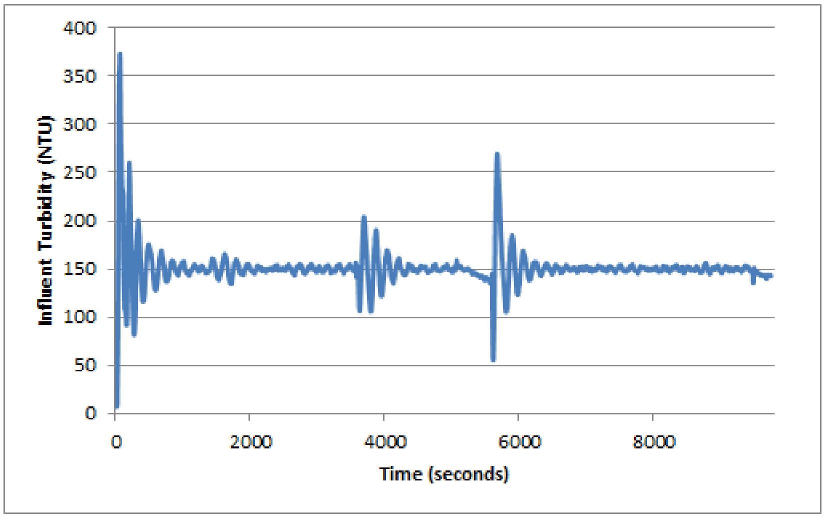

Figure 3: Influent turbidity to the flocculator over a period of 2.5 hours. The target turbidity for this test was 150 NTU, and the clay stock concentration was 75 g/L. P, I, and D values were 0.3, 0.3, and 0, respectively.

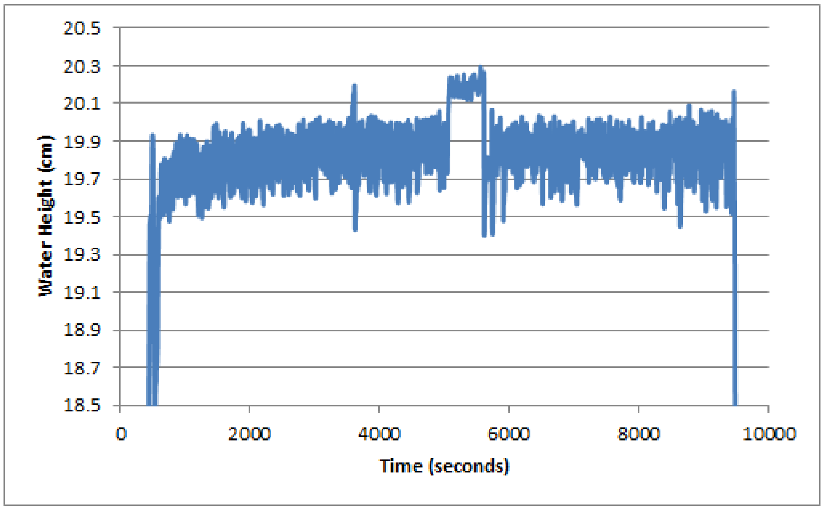

Figure 4: Height of water in the head tank over a period of 2.5 hours. The water level was kept approximately at the height of the overflow outlet, which is the height at which the system achieved a flow rate of 100 mL/s through the flocculator.

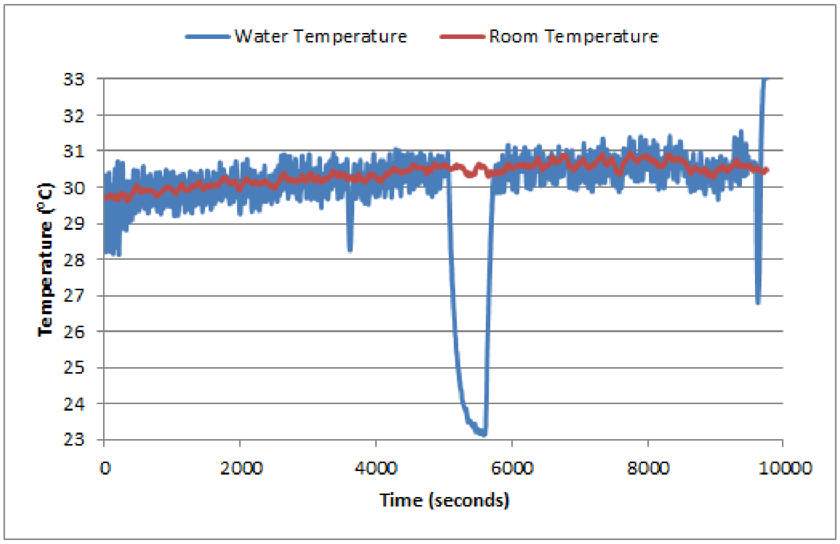

Figure 5: Water temperature in the head tank and room temperature over a period of 2.5 hours. The water temperature was maintained relatively equal to the room temperature, apart from the large downward spike at around 5800 seconds, but there was constant fluctuation as a result of using hot and cold water valves that operate separately.

Future Work

Further research and design work needs to be done in order to set up and implement a PID control system for clay dosage that can be reliably used during experimentation without experiencing significant errors. The team should then attempt to design 12 hour experiments for the turbulent tube flocculator. A peristaltic pump should also be installed to remove air from the SWaT. Additionally, experiments should be conducted on the turbulent tube flocculator to determine the effectiveness of the SWaT system.

References

[1] M. L. Weber-Shirk. Flocculation model. In *PowerPoint notes from CEE 4540*.