Tube Flocculator Team Final Research Report

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Abstract

According to the predictive flocculation model proposed by Swetland et. al., 2012, large flocs do not significantly contribute to turbidity removal – only small colloids can collide effectively and aggregate to a size that will be removed by sedimentation. Based on the hypothesis that "large flocs are useless", a floc breakup procedure was devised. Results obtained using a coiled tube flocculator and flocculation residual turbidity analyzer (FReTA) shows that higher turbidity removal was achieved after breaking the flocs, comparing to results using the same method but without floc breakup. Therefore breaking flocs at regular intervals to maintain continuous growth will promote better performance of flocculation. This research finding provided a good reference for future hydraulic flocculator design.

Key words: Tube flocculator, FReTA, flocs breakup, flocculation, coagulant dose, residual turbidity

Part I

Introduction

Mechanical flocculators are not economically and ecologically sustainable in terms of energy consumption, financial cost and carbon footprint. Gravitational or hydraulic flocculators, compared with Mechanical ones, are more cost-effective, reliable and energy efficient. However, for over a hundred years, hydraulic flocculators have been used less widely than mechanical flocculators due to marketing constraints and the impression that hydraulic flocculators are not flexible in their operation. The process of hydraulic flocculation has also not been well understood and the fundamental mechanisms that govern the performance of this process need to be further studied to improve design. Hydraulic flocculators can be divided into two types: Horizontal flow flocculators and Vertical flow flocculators. Horizontal flow is usually applied in small scale water treatment plants and is easy

to drain. Vertical flow flocculators are suitable for medium to large scale treatment plants.

Basically, the flocculation process is the coalescing of colloids or suspended particles to form flocs that can be removed by sedimentation. The goal of flocculation is to minimize residual turbidity or maximize turbidity removal. To improve the performance of flocculators, we need to research the design and operational parameters that affect the aggregation and setting velocity of the flocs. These parameters include energy dissipation rate, hydraulic residence time, sedimentation velocity, coagulant dose, influent turbidity, etc. Dead zones at the edge of baffles create regions where little or no collisions of particles occur. Thus, an ideal flocculator would have a uniformly distributed energy dissipation. Because of drag and shear forces, large flocs are more subject to breakup. The energy dissipation rate (ε) determines the maximum size of flocs because large flocs experience the greatest breakage at the maximum ε. One option to allow flocs to grow larger is to reduce ε by adjusting the spacing between the baffles. Variation in baffle spacing is called tapered flocculation. In tapered flocculation, a high energy dissipation rate is used initially to enhance collisions and low ε used later to prevent shear of large flocs.

In laminar flow, velocity gradient (G) is a function of $\varepsilon$and viscosity (υ). [5]

$$G = \sqrt{\frac{\varepsilon}{\nu}}$$

G=velocity gradient, the difference in velocity between adjacent layers of fluids

ε=energy dissipation rate, a measure of mixing intensity

υ= viscosity of water

Besides velocity gradient, the extent of flocculation is also related to how long the colloids are given to collide (i.e. hydraulic residence time (θ), fractional coverage of colloid surface by coagulant (Γ), and fraction of the total volume occupied by flocs (ϕ). The composite variable ($G\theta\Gamma\phi^{2/3}$) has been used by Swetland [1] to measure the collision potential (Ψ), which controls the extent of flocculation. Lower residual turbidity can be achieved by increasing the collision potential.

The sedimentation velocity of flocs determines the design of sedimentation clarifiers and plate settlers. High sedimentation velocity is an indicator of effective flocculation.

Theoretically, more collisions will occur in high turbidity water so the turbidity removal efficiency is higher when influent turbidity is higher.

Part II
Literature Review

1 Flocculation Model

The current design of flocculators is primarily based on empiricism and the fundamental understanding of flocculation mechanisms is insufficient. A predictive model that would show the relationships between the flocculation and dependent variables is expected to guide the design and operation of hydraulic flocculators. [3] The aggregation of small colloids into flocs is a first-order reaction with respect to the concentration of small colloids. [4]

$$\frac{d_{Colloids}}{d(Gt\Gamma\phi^{2/3})} = -kC_{Colloids}$$

$C_{Colloids}$= the concentration of colloids that can not be captured in the sedimentation tank

G = mean velocity gradient

θ=hydraulic residence time

Γ= fractional coverage of colloids by coagulant

ϕ= floc volume fraction

Swetland et. al. 2012 proposed a laminar flocculation model which is governed by the following equations.

pC*= - $\log(C^*)$ = $\log\left(G\theta\Gamma\phi^{2/3}\right)$= $\log\left[\frac{1}{\beta}\ln\left(\frac{C_{Colloids0}}{C_{Colloids}}\right)\right]$

where:

G = mean velocity gradient

θ=hydraulic residence time

Γ= fractional coverage of colloids by coagulant

ϕ= floc volume fraction

pC*= turbidity removal and C*= residual turbidity divided by influent turbidity

β= $\frac{\eta}{V_{Capture}}$, whereη is a fitted parameter, and V$_{Capture}$= capture velocity

$C_{Colloids0}$ = the original concentration of colloids

$C_{Colloids}$ = the concentration of colloids that can not be captured in the sedimentation tank

The log linear equation proposed by Swetland demonstrated the connection between colloidal particle properties, coagulant size and dose, flocculator design and sedimentation tank design. Fits to data using the assumption of first order removal of small colloids with respect to collision potential are shown below and agree well with experimental results (Figure 1). [1]

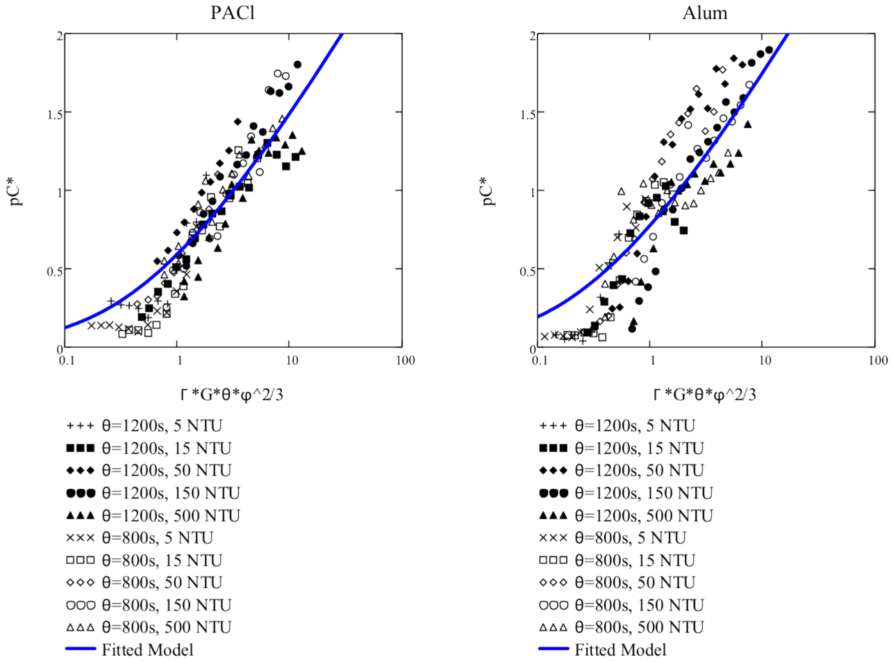

Figure 1 Model fit for pC* as a function of effective collision potential for $V_{Capture}$= 0.12 mm/s

2 Coagulation Mechanism

Coagulation is the process of coagulants (e.g. PACl, alum) attaching to clay particles. Conventional theory states that positively charged coagulants neutralize the negative charges on the particles to prevent particles from repelling each other. This assumes that when the repulsion between particles is reduced, the colloids can attach to each other and it does not consider that water may compete with coagulants to attach to colloids. Some research [2] also indicates that distinct mechanisms govern the behavior of common coagulants: alum

and PACl. For PACl, the major mechanisms include electrostatic patch and bridge-aggregation and charge neutralization. In contrast, alum is believed to interact with clay particles mainly through charge-neutralization and sweep-flocculation. Since the experiment results based on alternative theories yield very similar trends in residual turbidity verses coagulant dose (Figure 1), the distinct coagulation mechanism is difficult to discern. Experiments conducted by Swetland [3] showed that residual turbidity was decreased by a large amount with a slight increase of the coagulant dose and at high coagulant dose, no increase of residual turbidity was observed, as would be expected with charge reversal. An alternative hypothesis [4] involving adhesion of coagulant aggregates to colloids has provided a better explanation of coagulation. In this theory, the attachment force of adhesive aggregates produced by coagulants is stronger than the hydrogen bond between water molecules. Thus, these adhesive aggregates displace water to attach to the clay particles.

3 Apparatus

The complete experimental assembly consists of synthetic raw water (SRW) and coagulant metering system, rapid mix and tube flocculator, and flocculation residual turbidity analyzer (FReTA). (Figure 2) The turbidimeter with a feedback loop is used to measure the influent turbidity and the turbidimeter of FReTA measures the effluent turbidity.

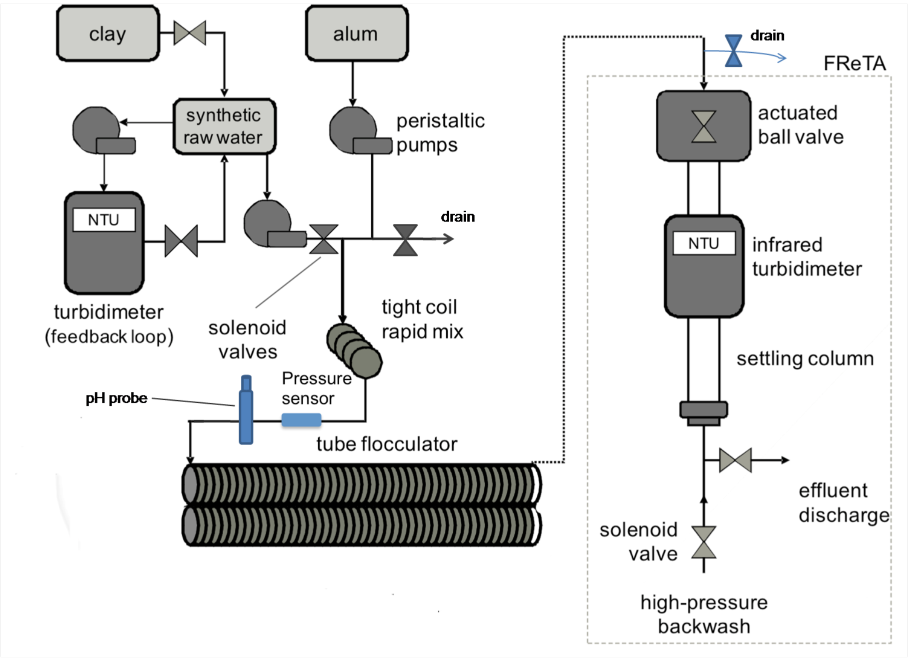

Figure 2 Schematic of the complete experimental assembly. (Updated from Ian Tse's MS thesis, Aug. 2009)

3.1 SRW and coagulant metering system

The SRW and coagulant metering system includes a reservoir of clay suspension (10g/L), a reservoir of tap water and three pumps (Figure 3). The clay suspension is added to the tap water periodically by the regulation of a solenoid pinch valve. Both alum stock and raw water (with added clay suspension) are drawn by the pumps to mix together. A portion of raw water is pumped into a turbidimeter for the measurement of influent turbidity and then flows back into the raw water feedstock to maintain a constant volume. A flow accumulator connected to the pump dampens the periodic pulses caused by the pump rollers.

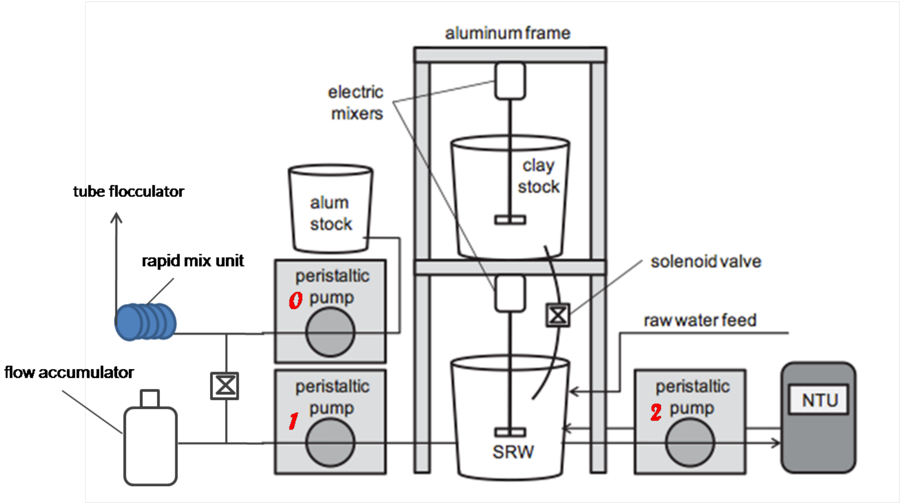

Figure 3 Synthetic Raw Water (SRW) and coagulant metering system. (Updated from Ian Tse's MS thesis, Aug. 2009)

3.2 Rapid Mix and Tube Flocculator

After the flow of the raw water and alum is merged, they enter into a spiral "rapid mix coil " to accelerate their blending. The mixture then flows through the laminar tubular flocculator. The tube flocculator is comprised of three spiral tubing units (3/8") wrapped in a figure eight around six parallel support cylinders (two cylinders per unit, see figure 4). The tubes are arranged in a helical coil because the flocs would stay at the bottom in a straight tubing system, restricting the growth of the flocs. A calibrated in-line pH probe is inserted at the beginning of the flocculator tube and provides a readout of the mixed suspension's hydrogen ion activity. A pressure sensor is also connected to the tubing to protect the system. Velocity gradients in the tubular flocculator cause particles to collide and form flocs. For coiled tube flocculators, velocity gradient is a function of the flow rate and the inner diameter of the tube. [5]

$$G = \frac{8Q}{3\pi r^3}$$

G = velocity gradient
Q = volumetric flow rate
r = inner diameter of tube

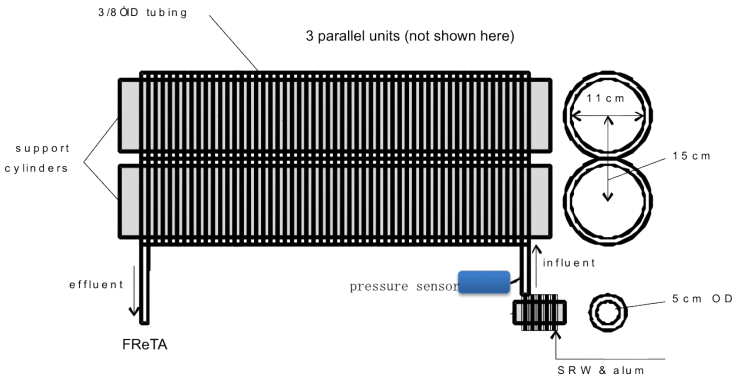

Figure 4 Tube flocculator. (Updated from Ian Tse's MS thesis, Aug. 2009)

3.3 FReTA

FReTA is an apparatus for measuring the sedimentation velocity and the effluent residual turbidity from the flocculator (Figure 5). There are basically three components of FReTA: an inline turbidimeter, a settling column, and an computer-actuated ball valve. The plastic housing of the HF Scientific MicroTOL 2 IR inline nephelometric turbidimeter was changed in our apparatus to allow a glass column to fit through the entire housing and through the measurement area. Before use, FReTA is carefully calibrated using a HF Scientific, Inc. Primetime Calibration Standards kit.

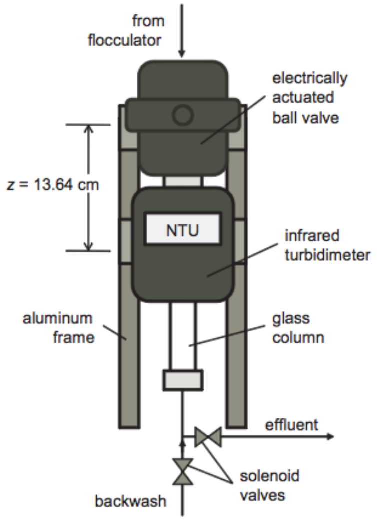

Figure 5 FReTA. (From Karen Swetland's dissertation, Aug. 2012)

The glass settling column serves as a chamber for floc settling without affecting the structure of flocs. Before measurement of floc settling velocity, it is important to minimize the movement of fluid inside the column. This is accomplished by ramping the flow to a stop and closing the valve at the top of the tube.

The function of the electrically actuated ball valve (Gemini Valve model 630) was to prevent flocs in the tube flocculator from falling into the settling column once the measurements begin and to hydraulically isolate the water in the tube. The distance between the bottom of the ball valve and the center of the LED zone of the turbidimeter is used to calculate floc settling velocities. The equation for sedimentation velocity of flocs is given below. [1]

$Vs = \frac{Z}{t}$

Vs = sedimentation velocity

Z = distance between the bottom of the ball valve and the center of the LED zone of the turbidimeter

t = settling time

Part III

Tube Flocculator Research

The goal of Tube Flocculator Research is to develop flocculation models in laminar flow and to determine different parameters that affect the flocculator performance in order to achieve the lowest effluent residual turbidity. The first step for research in Fall 2012 was to repeat Dr. Karen Swetland's flocculator experiment with alum to get a baseline curve of turbidity versus dose for comparison to subsequent experiments. In this baseline data the residual turbidity will be measured over a range of chemical doses for a spectrum of sedimentation capture velocities. In subsequent experiments the residual turbidity will be measured under the same experimental conditions but with breakup of large flocs at regular intervals. [6]

4 Hypotheses

1. Only laminar flow occurs in tube flocculators.

2. Colloids cannot attach to large flocs at maximum size thus we need to break those flocs to maintain continuous growth.

3. At low coagulant doses, the residual turbidity is relatively high because the attachment efficiency is not big enough to allow flocs to form. With the increase of coagulant dose, attachment efficiency rises so the residual turbidity is lowered.

4. Discrete settling is assumed in analysis of data since the distance Z is much less than the 0.5m interval between sampling ports used in conventional flocculant settling tests. [5]

5. Flocs will collide and grow when they travel from one breakup position to another.

6. Broken flocs can aggregate with small colloids with the same attachment efficiency.

Part IV
Methods and Materials

5 Methods

5.1 Process Controller

Experiments were conducted by the apparatus described above. The apparatus assembly is managed by Process Controller, a software program written in LabVIEW to automatically control the whole experiment. There are six operational states regulated by Process Controller to run the experiment. Each of these states consists of a different set of inputs, rules and set points. The description of each state is provided in Table 1. This table provides a reference for operators to check if the rules and states are set correctly and what set points to search when they meet problems. At "automatic operation" mode, the experiment proceeds continuously from the first stage to the last state and then jumps back to the first state for the next cycle. The number of cycles is set by the operator at the set point " Max reps". According to the rules for the settling state, when the number of reps is bigger than the Max reps, then the experiment will stop. The collected data is recorded and processed on a spreadsheet in a MathCAD program called Data Processor.

Table 1. Process Controller Operational States

State Name	Function	Rules	States (only ON state is shown here)	Related Set Points	Duration	Note
1. Backwash	Rinse the whole system to dislodge clay and air bubbles.	**IF** Elapsed time in current state > 1. Total Backwash Duration, then go to *state 2*	Only 2 Pump is running and The valve control backflow is ON	Backwash flow rate Backwash Multiple Back wash residence time Total backwash duration Influent turbidity	797.4192s	Water flow backwards from settling column to drain.
2. Loading State	Raw water (with clay) and coagulants are mixed together to travel to the tube flocculator.	**IF** Elapsed time in current state > 2. Total Loading Duration, then go to *state 3* **OR IF** Rep counter > Max reps, then go to *OFF*	0 Pump is running if alum dose is NOT zero and its speed is controlled by set point "alum pump control" 1 Pump and 2 Pump is ON. Valve influent to floc is ON and Valve effluent to column is ON.	Plant flow rate Loading residence time Residence time multiple Total loading duration Alum stock concentration Alum dose Alum flow rate Alum tubing size Alum # of heads Alum pump control Raw water pump control Raw water flow rate Raw water tubing size Raw water # of heads Rep counter	2174.78s	Alum dose is determined by Alum reset state, Alum state in increment, alum slope, alum intercept and alum Max X.
3. Pump Ramp Down	0 Pump and 1 Pump slowly come to a stop to avoid vibration that causes vortex in the settling column.	**IF** Elapsed time in current state > 3. Ramp Down Duration, then go to *state 4* **OR IF** Pressure Sensor Value >= 600, then go to *OFF*	All three pumps are ON and 0 Pump is controlled by set point "alum ramp down control". Valve influent to floc and Valve effluent to column are ON.	Ramp down final value Ramp down constant Ramp down duration RW ramp down control Alum ramp down control	30.875s	Flow deceleration (Ramp down constant) is 3.5 cm/s^2
4. Shutoff Ball Valve	Block the connection between flocculator and settling column for measurement of settling velocity	**IF** Elapsed time in current state > 4. Ball Valve Duration, then go to *state 5*	2 Pump is ON and valve influent to floc, valve effluent to column and ball valve are ON.	Ball valve duration	6s	The flow in the system is completely stopped to ensure no breakage of flocs through the orifice.
5. Settling State	Flocs settle in the settling column. Effluent turbidity is measured under quiescent condition.	**IF** Elapsed time in current state > 5. Settling State Duration, then go to *state 6*	0 Pump is ON. Valve effluent to column and ball valve are ON.	Settling state duration Effluent turbidity	1800s	
6. Open Ball Valve	Recover the connection between flocculator and settling column to prepare for the next cycle.	**IF** Elapsed time in current state > 4. Ball Valve Duration, then go back to *state 1*	0 Pump is ON. Valve influent to floc and valve effluent to column are ON.	Ball valve duration	6s	

5.2 Experimental Method

All experiments conducted are using the same method recorded in AguaClara's archive with the following directory: N://files.cornell.edu/EN/aguaclara/RESEARC

Floc/Spring 2012/Experiments/6-29-2012. The specific description of this method is provided below.

Table 2 Experimental Method Fall 2012

Set Point	Value
Target influent turbidity max	100 NTU
Target influent turbidity min	99.7 NTU
Raw water flow rate	5.5 mL/s
Length of tube	83.88 m
Alum base	1.3
alum coefficient	1.5
Max reps	15
Alum stock conc.	700 mg/L

Note: A power law relationship is used to set a range of alum dose to spread out the residual turbidity vs. dose curve. This equation shows how we set the dose of alum:

Alum dose $= coefficient \times (base)^{maxreps}$

Where max reps means the number of experimental cycles, which is set by operators. [8]

6 Material List

Raw water: Dayton Motor (Grainger #3M290); Bucket; Cylindrical Polypropylene Float (Robert Manufacturing Company); Tubing inlet/outlet for influent turbidimeter (1/4"); Tubing outlet for system (3/8"); valve;

Clay water: 10 g/L clay solution; Bucket Tubing outlet to raw water (1/16"); Farmington pinch valve; Stand (made of 1"X1" 80/20);

Alum water: 2.5 g/L aluminum sulfate solution; Tubing outlet for alum dosage (1/4"); valve

Alum pump: L/S Peristaltic pump (Cole-Parmer); Tubing to alum water: 1/4" flexible; Tubing to system: 1/4" rigid

Influent turbidimeter pump: L/S Peristaltic pump (Cole-Parmer); Tubing: 1/4" rigid

System pumps: L/S Peristaltic pump (Cole-Parmer) – four channels Tubing: 3/8" rigid

Influent Turbidimeter: Wooden stand MicroTol Online 2 Turbidimeter (#20053)

Input to system: 1/4" T combining alum and raw water to enter system; plastic bottle, drilled for tubing to act as actuator; 3/8” – 1/4" reducers; Pipe thread valve (Farmington); Rapid mixing: rigid tubing (1/4”); wrapped around a 2.5” diameter cylinder; 1/4"-3/8” expander; 3/8”-1/2” expander; 1/2" T (1 end has valve to dislodge bubbles); Pipe thread valve (Farmington)

System: ˜9000 cm flexible 1/2" tubing; Ball valve (Gemini #630); MicroTol Online 2 Turbidimeter (#20053); Glass column (12” length, 1” od, 0.82” id); Brass elbow; Rigid tubing to sink / backwash (3/8”); 3/8” T to sink / backwash; 2 Pipe thread valves (Farmington), sink / backwash; Water source for backwash. [7]

Part V

Results and Analysis

7 Control Experiments

The control experiments were replicated using the method described in Section 5.1. Figure 11 shows that the mean influent turbidity stayed around 100 NTU with a increased concentration of alum, while the mean effluent turbidity during loading state had an upward trend with escalation of alum dose. This may mean that alum and flocs are accumulating on the walls of the flocculator over time and that the concentration in the flow gradually increases as the available wall surface gets covered. The effluent turbidity jumps from a background value of around 0.3 NTU, to about 70 NTU. Figure 12 reveals that the residual turbidity decreased from about 55 NTU to 10 NTU with alum dose increasing from 0–8 mg/L. The increase of residual turbidity at the third cycle and the last cycle might be caused by the movement of some tiny flocs at the measuring region of turbidimeter, which makes the number vary a little. As time goes on, the residual turbidity generally declines but it’s hard to tell the difference of removal efficiency with 0.1 mm/s capture velocity changing gradually to 0.5 mm/s (Figure 13).

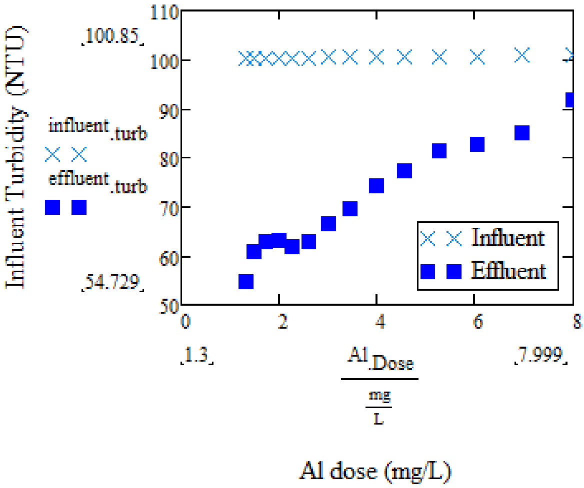

Figure 11 Influent and effluent turbidity vs. alum dose at loading state for each experiment cycle

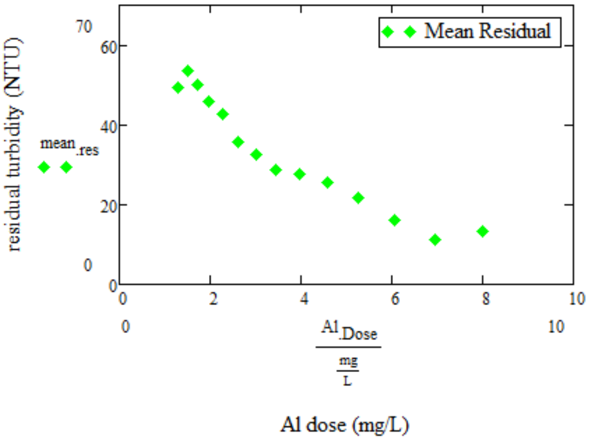

Figure 12 Residual turbidity vs. alum dose

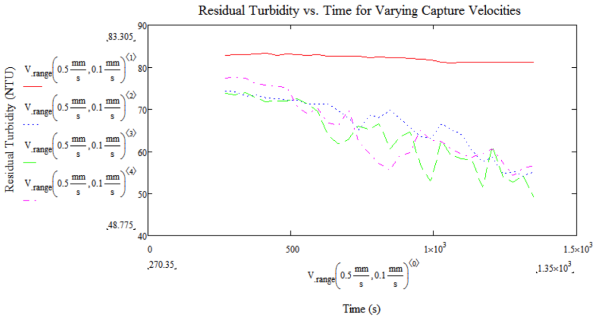

Figure 13 Residual turbidity vs. time for 0.1 mm/s to 0.5 mm/s capture velocities

8 Experiments with floc breakup

A floc breakup procedure was devised according to the calculations of energy dissipation rate, capture velocity, collision time. Six hose clamps were evenly placed onto tube flocculator (2 on each unit, see figure 14). The inner diameter of clamps are calculated based on the maximum energy dissipation rate. After the floc breakup device were set up, the flocculator were cleaned using a tiny sponge to remove the clay that sticked to the walls of flocculator. Then a complete experiment with the same method as the control experiment was conducted.

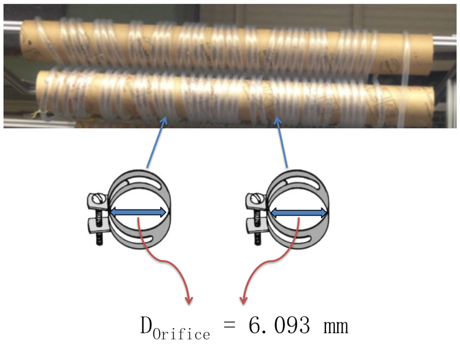

Figure 14 Floc breakup installation

Figure 15 demonstrates the compared results of residual turbidity with floc breakup and without floc breakup. Obviously, the residual turbidity are lower when breaking the flocs using clamps. At the alum dose 4, 4.6 and 5.2 mg/L, the difference of residual turbidity curve reaches 10 NTU. Both curve seems to fit into the logarithmic trend line – the one with floc breakup matches the trend line with

a correlation coefficient of 0.99. These two trend lines are consistent with the predictive model in Chapter 1. The results indicate that our hypothesis "large flocs are useless" is correct and offers insight into improving AguaClara's current flocculator design.

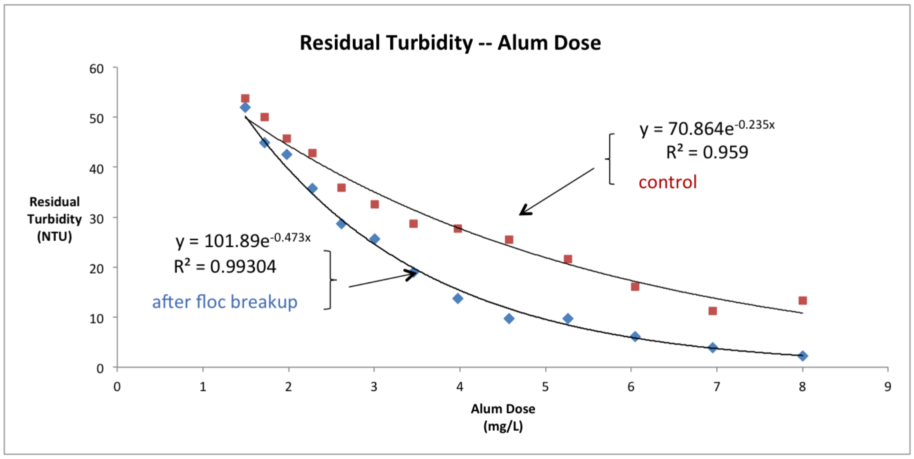

Figure 15 Comparative results of resitual turbidity vs. alum dose

Part VI

Conclusions

9 Breaking flocs and flocculator design

The capacity of flocculator is based on it's ability to cause collisions between particles. Breaking large flocs that allow more collisions to happen may be helpful to achieve higher turbidity removal. Thus, for laboratory experiments, we need to design a component that can break up flocs at regular intervals. This special component can be an orifice, or a wire mesh set at a size that correlates with a desired energy dissipation rate.

10 Problems and Solutions

10.1 Problems with tubing and connectors

1. When the connections of tubes are leaking, you should check the tubes to make sure they are fully plugged into the connectors– the tube can not be easily pulled out if it is fully inserted. To ensure no leaking, you need to verify each connection is robust before beginning

the experiment. If there is a leak at the top of the settling column, stop any experiment and drain the column. You may need to remove the turbidimeter to adjust the connection.

10.2 Problems with apparatus

1. If the apparatus is not on when you turn on the switch, that is because the power strip sometimes trips the GFI protection. When you meet this problem, press the GFI reset button which is on the outlet behind the water tank.

2. If raw water pump is not running at loading state, check the direction of flow at that pump (should be towards the rapid mix) and the mode (should be on mA).

3. If influent turbidity is too high (meaning it is at least 10 NTU more than the target turbidity max), use a 1L plastic container to scoop up some water from the raw water bucket. This water will be replaced by clean tap water to keep the volume constant and you should seethe turbidity go down. The influent turbidity should decrease by at least 15 NTU after you remove 1L of dirty water. The water in the raw water bucket gets dirtier and dirtier with clay addition. It is hard to insert another tube to drain the water so water that is too turbid must be removed manually before an experiment is started.

4. If the alum pump is not running at loading state, first ask yourself if this is the first cycle. If it is the first cycle, then this is normal because the alum dose is set to be zero at the first replication. If it's not the first cycle, go to settling state and then click loading state to see if the alum dose has an increment. If there is an increment, then the valve (between the rapid mixer and raw water pump) may be mistakenly closed. If it is not, then check if the set points are set correctly by locating the set points at rule editor to ensure the variables match the code.Process Controller Set Points used to control the experimental apparatus. Variables are listed with their virtual instrument code (.vi) and can all be found in the folders located at the following directory path: \\Enviro\enviro\Software\Process Controller methods

5. If water is filling up the flow accumulator, check the cap of the accumulator to make sure it's tight.

10.3 Problems with Process Controller

1. If you turn on all the switches, and none of the green indicator lights on Process Controller are on, that means you are not connecting

with the right server or the server may have crashed. Check the main server to make sure it is functioning properly and check the data server on Process Controller (should be "aguadata.cee.Cornell.edu").

2. When you're operating from one state, sometimes nothing is shown on the "current state" and the "state list" is not shown at "rules and states" at the next state. When this happens you need to reload the method file and save it in your experiment folder.

10.4 Problems with Data Processor

1. If you're having trouble loading the data from Metafile of Data Processor, first you need to check the directory to make sure it's on the right track to locate the Metafile (an excel spreadsheet in the "data processor" folder). Second check all of the information for a certain MetID (the one retrieves your experiment). Pay attention to the dates and duration (if your experiments span 2 days, you need to put in the both dates and a duration of 2).

2. Sometimes the graph on the MathCAD file of Date Processor is not shown due to memory loss, then you may have to restart the computer to reload the data.

Part VII

Future Work

1. Because alum and flocs are accumulating on the walls of the flocculator and backwash with tap water is not enough to get rid of all of them. We need a way to remove the alum to eliminate the possibility that alum sticked on the tube walls causes the residual turbidity to go down. Add a new state to rinse the flocculator with a dilute acid to dissolve the coagulant to ensure all of the experiments have the same starting point with a clean flocculator tube. Then carefully repeat this semester's experiments to see if the results have any change.

2. Try different floc breakup intervals to determine optimal spacing of orifices or clamps.

3. Test tapered flocculation which is realized by reducing the energy dissipation rate gradually so that the flocs are able to grow.

Reference

1. Karen A. Swetland, From stock to floc: an investigation into the physical/chemical processes controlling aluminum sulfate and polyaluminum chloride behavior in a gravity powered drinking water treatment plant, Ph.D. dissertation, School of Civil and Environmental Engineering, Cornell University, Aug. 2012, pp.119.

2. Xiaohong Wu et. al. , Distinct coagulation mechanism and model between alum and high Al13-PACl, Colloids and surfaces A, 305, 2007, pp. 89-96.

3. Karen A. Swetland, Monroe L. Weber-Shirk, Leonard W. Lion, Predictive performance model for hydraulic flocculator design with polyaluminum chloride and aluminum sulfate coagulants, School of Civil and Environmental Engineering, Cornell University, 2012.

4. Monroe L. Weber-Shirk, Class notes, CEE 4540 Sustainable Municipal Drinking Water Treatment, School of Civil and Environmental Engineering, Cornell University, Oct. 2012.

5. Ian Tse, fluid shear influences on hydraulic flocculation systems characterized using a newly developed method for quantitative analysis of flocculation performance Master of Science thesis, School of Civil and Environmental Engineering, Cornell University, Aug. 2009, pp.92.

6. Flocculation with FReTA, Design Challenge for Tube Floc Team Fall 2012, AguaClara Project, School of Civil and Environmental Engineering, Cornell University, Aug. 2012.

7. Karen A. Swetland, Materials List for the FReTA Apparatus, Tube Floc research, AguaClara Project, School of Civil and Environmental Engineering, Cornell University, Jun. 2010.

8. Monroe Weber-Shirk, An Automated Method for Testing Process Parameters, AguaClara Project, School of Civil and Environmental Engineering, Cornell University, Jun. 2010.