High Shear Flocculation

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Introduction

The efficiency of a water treatment plant is primarily indicated by the performance of the flocculator. In a turbulent flocculator, most clay particles successfully collide to form a floc. These larger flocs of clay particles are then easily settled out in the sedimentation tank and captured in the sand filters.

Research has shown that larger clay particles can only collide and stick to other large clay particles [1]. Through this research, it has been hypothesized that smaller clay particles (roughly 7 micrometers in diameter) cannot aggregate with a large floc, due to the large viscous layer around the larger particles.

Group 8 tests the hypothesis above through designing a flocculator system with a high enough shear to break apart the larger flocs. This high shear will give the primary clay particles a higher chance of collision and, thus improved ability to form flocs.

Addressing the escaping primary clay particles is essential because surface water treatment plants are unable to produce treated water with a turbidity of less than 0.1 NTU. It is assumed that the escaped primary particles are typically too small to be captured in following treatment processes. It is crucial to have treatment plants produce water that is less than 0.1 NTU to deliver cleaner water. If successful aggregation of almost all clay particles can occur, and the turbidity is decreased, the hypothesis will be proven correct. If the results are unsuccessful, then that could point to a flaw in the experimental apparatus or the teams understanding of particle collision.

Objectives

With the assumption that smaller flocs can only aggregate to other similar sized flocs, the team decided to decrease the overall size of flocs within a coiled flocculator. The chances of aggregation will increase using the coiled flocculator, thus decreasing the number of particles that have not been flocculated.

Fluid shear controls the collision of clay particles in a turbulent flocculator. The equation for fluid shear is shown below:

$$\tau(y) = \mu \frac{\partial u}{\partial y}$$

where μ is the dynamic viscosity of the fluid, and $\frac{\partial u}{\partial y}$ is the fluid velocity above the boundary changing with the distance of height about the boundary.

The changing fluid velocity is also known as the velocity gradient, G. Therefore, fluid shear can be manipulated by changing the value of viscosity or the fluid velocity gradient, G. It is proposed that a higher shear rate in a laminar flocculator will increase the performance of the flocculator.

The equation for the number of sequential collisions that result in aggregation, N_c, is shown below:

$$dN_c = \pi \frac{{d_p}^3}{\Lambda^3} G\alpha dt$$

where d_p is the particle diameter, Λ is the initial distance between particles, G is the velocity gradient, α is a constant that is the fraction of particle covered by the coagulant, and t is time.

The value of dN_c scales with G. Once differentiated, there will be a Gt term, where t is time; t can also be known as residence time, θ. Collision potential is known as $G\theta$. Therefore, in order to increase the collision potential, the team varied $G\theta$. The team chose a high G value, for a high shear, and varied θ. Residence time was varied according to:

$$\theta = \frac{V}{Q} = \frac{L * A}{Q}$$

where V is the volume of the coiled flocculator, L and A are length and area of the coiled flocculator, respectively, and Q is flow rate.

By changing the length of the coiled flocculator, the team was able to vary $G\theta$.

A higher shear will limit the growth of clay particles, therefore increasing the chance that the particles will aggregate with one another. If the clay particles are not able to get so big such that smaller clay particles cannot attach to them, it is assumed that almost all primary clay particle will be captured and removed during sedimentation and sand filtration.

The core idea is that a higher shear might make it possible for clay particles to have more successful collisions with flocs because it will limit the growth of large flocs. With a higher shear, the team proposes that the chances particles aggregate to one other will increase and that almost all the flocs will then be removed during sedimentation and filtration. If correct, the measured turbidity should be lower than 1 NTU.

Previous studies have been done that show that high shear flocculation for a limited amount of time increases the size of particles leaving the flocculator. The study used inorganic cationic micro-particles as a coagulant for flocculation [2].

Procedures

Creating a coiled tube flocculator gave a scaled down model of a laminar flow flocculator. The tube flocculator was built in such a way that the values of particle collision, $G\theta$, could be manipulated.

The Materials used were: 3/16 inch diameter flexible tubing, tube cutter, cylinder base frame, peristaltic pumps, and 6 liter and 1-liter containers.

The following procedures were performed:

1. Several different values of $G\theta$ were chosen to determine flocculator lengths (reference Python Code "Varying G and θ").
2. The longest length flocculator was cut, and the shorter lengths were marked using tape.
3. One end of the flocculator was secured onto a cylinder and coiled around.
4. The tubing was connected to the peristaltic pump.
5. The experiment was run with ProCoDA.

Cleaning Procedures

Between experiments, the apparatus went through a cleaning procedure to prepare for the next experiment. The flocculator, the water stock tank, and the influent turbidimeter were cleaned.

1. Once the experiment is over, stand the flocculator up so that the end closest to the influent turbidimeter is higher than the water level in the water stock tank.
2. Unplug the connector between the flocculator and influent turbidimeter and put a plug in the flocculator.
3. Take the cuvette out of the turbidimeter and unscrew it.
4. Empty the cuvette into the sink, wash it twice with deionized water and then fill it with tap water.
5. Screw back in the cuvette and wipe the entire cuvette with a wipe.
6. Check to make sure the cuvette is not leaking and place it back into the turbidimeter.
7. Replace the coagulant stock tank plug that is connected to the water stock tubing with a normal plug.
8. Take the water stock tank and flocculator to the sink.
9. Empty remaining water in the stock tank and disconnect it from the flocculator.
10. Wash out the stock tank with tap water.

11. Drain the flocculator and run clean water through it once.
12. Reconnect the water stock tank and flocculator.
13. Pour water into the stock tank until it drains into the flocculator to prevent air bubbles in the system.
14. Reconnect the coagulant stock tank.
15. Reconnect the flocculator to the influent turbidimeter.

Hurdles/challenges

The challenges were time-related and communication-based. The main hurdle was determining the parameter to change. The goal was to vary one parameter and keep everything else constant. The parameter of interest was the shear in the flocculator. Initially, the team wanted to manipulate the diameter of the tubing to get a wider range of shear values but realized that there was not a good range of different tube diameters.

The team varied $G\theta$ to be 1000, 5000, and 10000. These values were chosen after consulting the AguaClara High G Floc team. The shear had to be high enough to prevent coagulant nanoparticle deposition on the flocculator walls; the High G Floc team had previously researched these values. Also, the values were chosen due to the amount of available tubing.

Another primary challenge was the volume of the stock tank. Because the coagulant nanoparticles required time for diffusion to clay surfaces, the experiments had to run for a few hours. However, the 6 L tank was not enough to run for a sufficient period, so the run times had to be cut short.

Lastly, it was difficult coordinating with another group when running experiments because the apparatus was controlled by their ProCoDA. There were problems with the other team's apparatus, so it took time to correct.

Results

The team anticipated that a high shear flocculator would allow less primary particles to make it through the flocculator without colliding with flocs and other particles. The particles will be able to attach to medium sized flocs since large flocs will not be able to be created due to the high shear. Primary particles are theorized to have a better chance of attaching to medium sized flocs rather than large-sized flocs. Table 1 lists all the key parameters, average turbidities, and average pC^* for each experiment.

Table 1: The parameters for each experiment.

$G\theta$	Flocculator Length (m)	Average Influent Turbidity (NTU)	Average Effluent Turbidity (NTU)	Average pC^*
0 (Control)	0	12.98	1.32	1.81
1,000	0.768	5.22	1.27	2.28
5,000	3.84	10.33	1.26	1.41
10,000	7.683	7.73	1.26	2.10

Figure 1 graphs the influent and effluent turbidity for $G\theta = 1,000$. Around 0.5 hours into the experiment and 1.2 hours into the experiment, there are spikes in the influent turbidity; these are believed to be caused by air bubbles entering the turbidimeter. The average influent turbidity for this experiment was 12.98 NTU, and the average effluent turbidity was 1.32 NTU.

Figure 2 shows the influent and effluent turbidities for $G\theta = 5,000$. The average influent turbidity was 5.22 NTU, and the average effluent turbidity was 1.27 NTU. Figure 3 shows the influent and effluent turbidities for $G\theta = 10,000$. The average influent turbidity was 10.33 NTU, and the average effluent turbidity was 1.26 NTU.

The team also ran a control experiment. This experiment had no flocculator but continued to pump coagulant, and the humic acid, clay, water mixture into the apparatus. Figure 4 shows the influent and effluent turbidities of the control experiment over time. The average influent turbidity was 7.73 NTU, and the average effluent turbidity was 1.26 NTU.

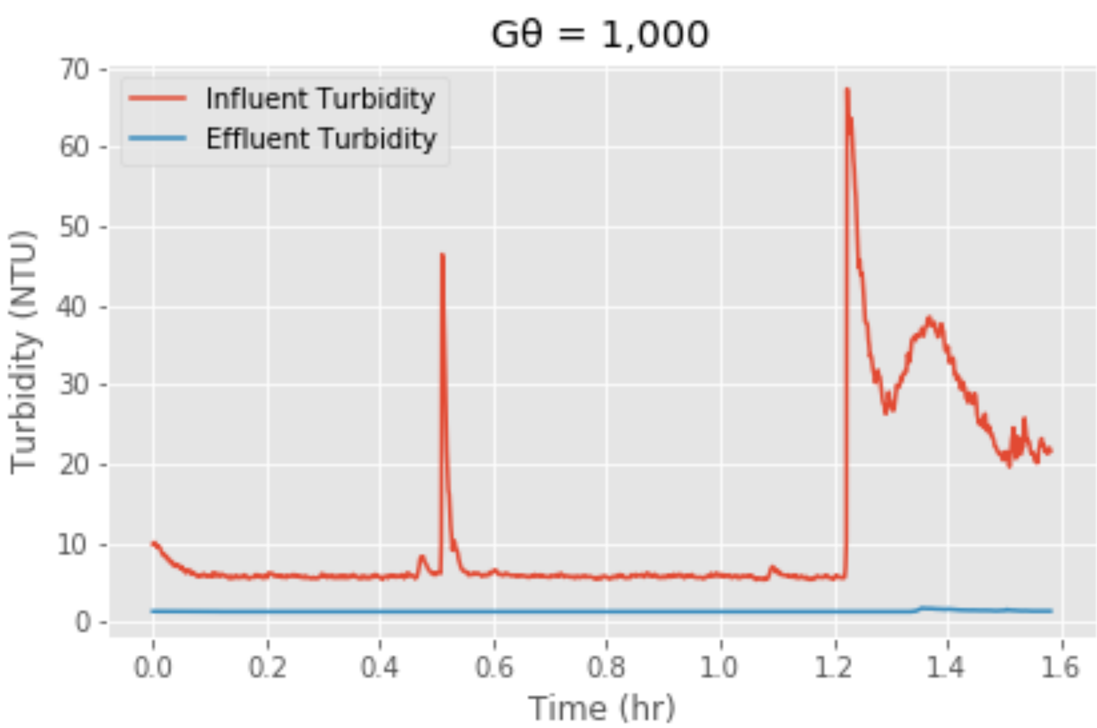

Figure 1: Influent and Effluent Turbidity verses time where $G\theta = 1,000$.

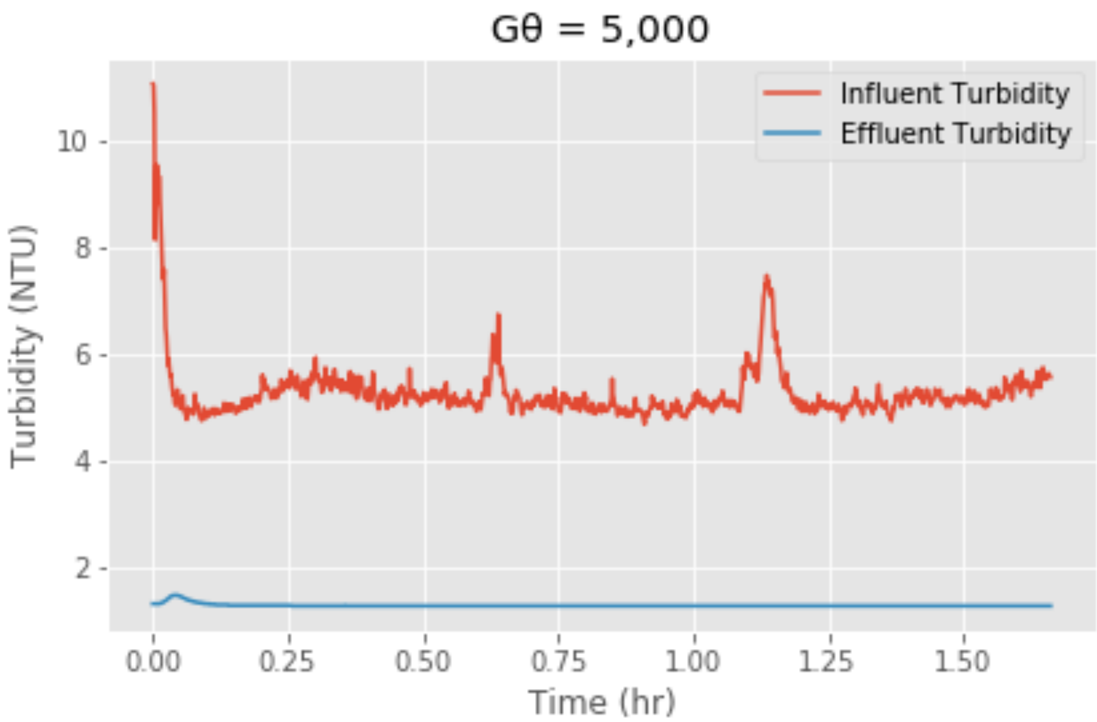

Figure 2: Influent and Effluent Turbidity verses time where $G\theta = 5,000$.

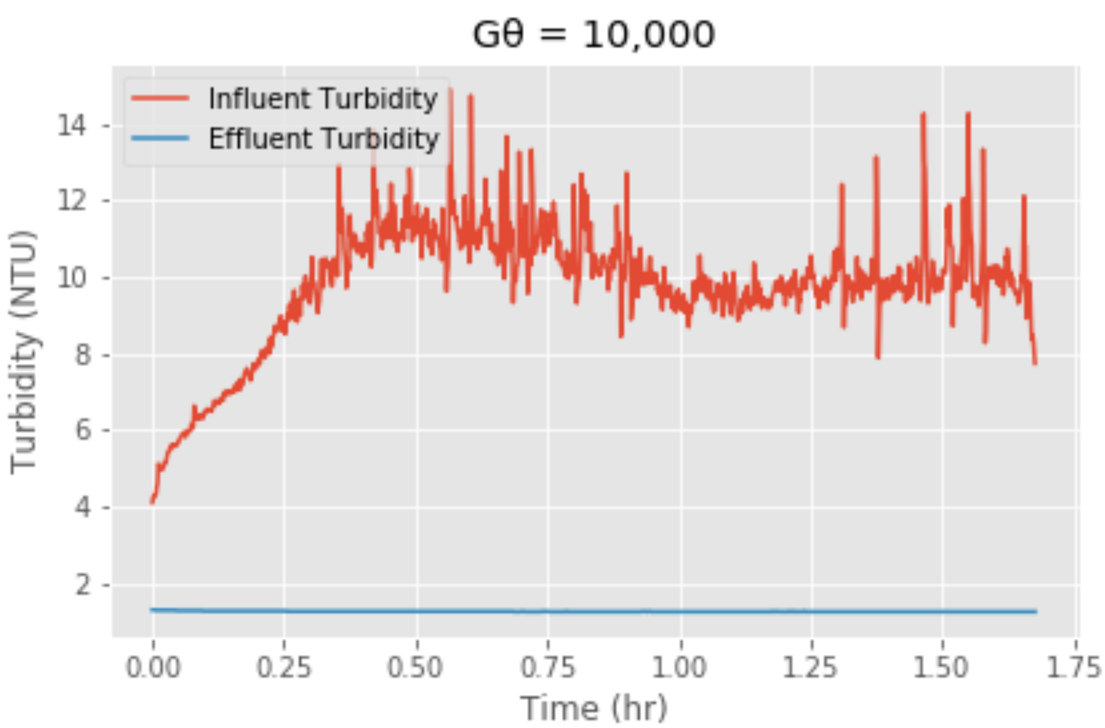

Figure 3: Influent and Effluent Turbidity verses time where $G\theta = 10,000$.

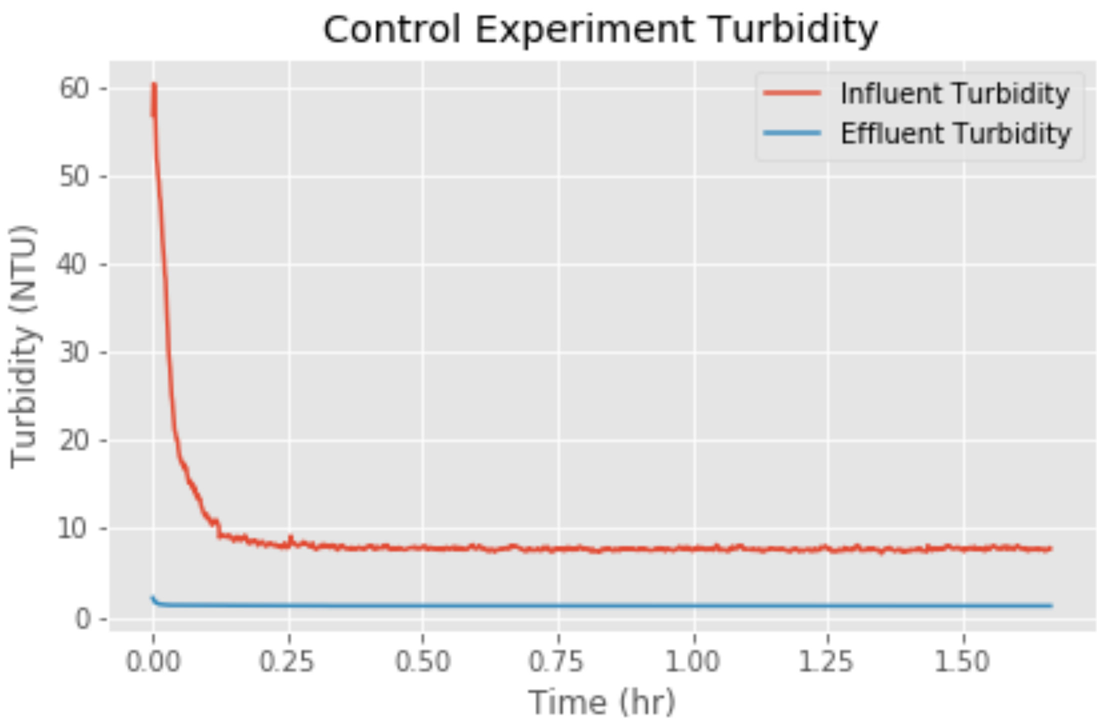

Figure 4: Control experiment, there was no flocculation, just a mixture of coagulant and clay, humic acid and water.

The average effluent turbidities for each experiment was plotted against the flocculator length and shown in Figure 5. These turbidities only range in a 0.06 NTU, and therefore there are no significant differences in the effectiveness of our flocculator.

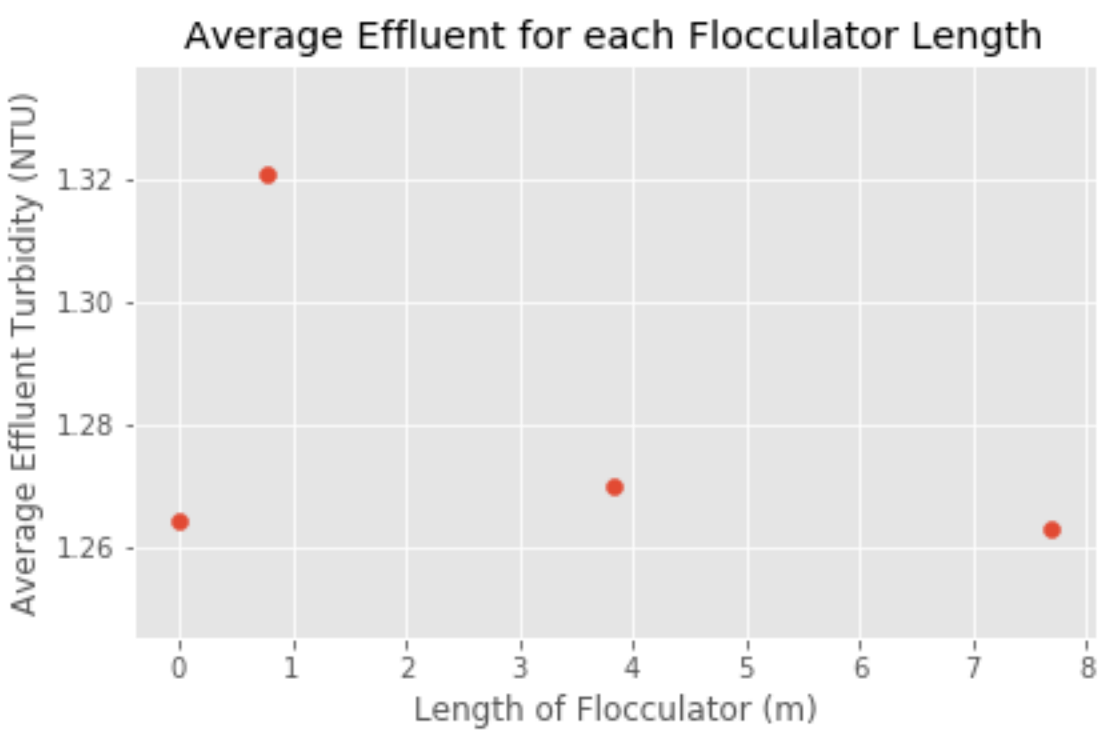

Figure 5: The average effluent turbidity for each flocculator length.

Since each experiment had a different influent turbidity, the team decided to look at the pC^* of each. This dimensionless parameter is defined as:

$$pC^* = -log\frac{(Effluent\ Turbidity)}{Influent\ Turbidity}$$

Figure 6 shows the plotted pC* for each experiment versus time. There seems to be no relationship between the pC* and $G\theta$. Since the team altered the length of the flocculator, the team plotted the average pC* for each flocculator length, shown in Figure 7. Figure 7 especially shows that there is no clear correlation between the length of the flocculator tubing and the performance of our filter.

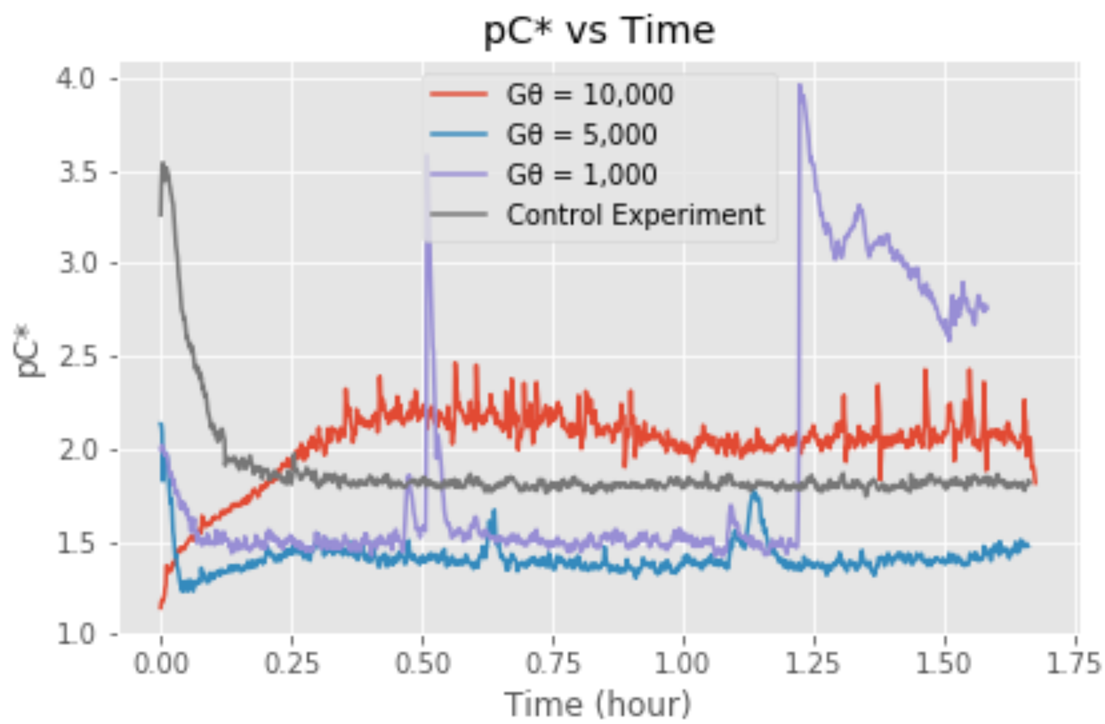

Figure 6: This *pC* * versus time for all four experiments.

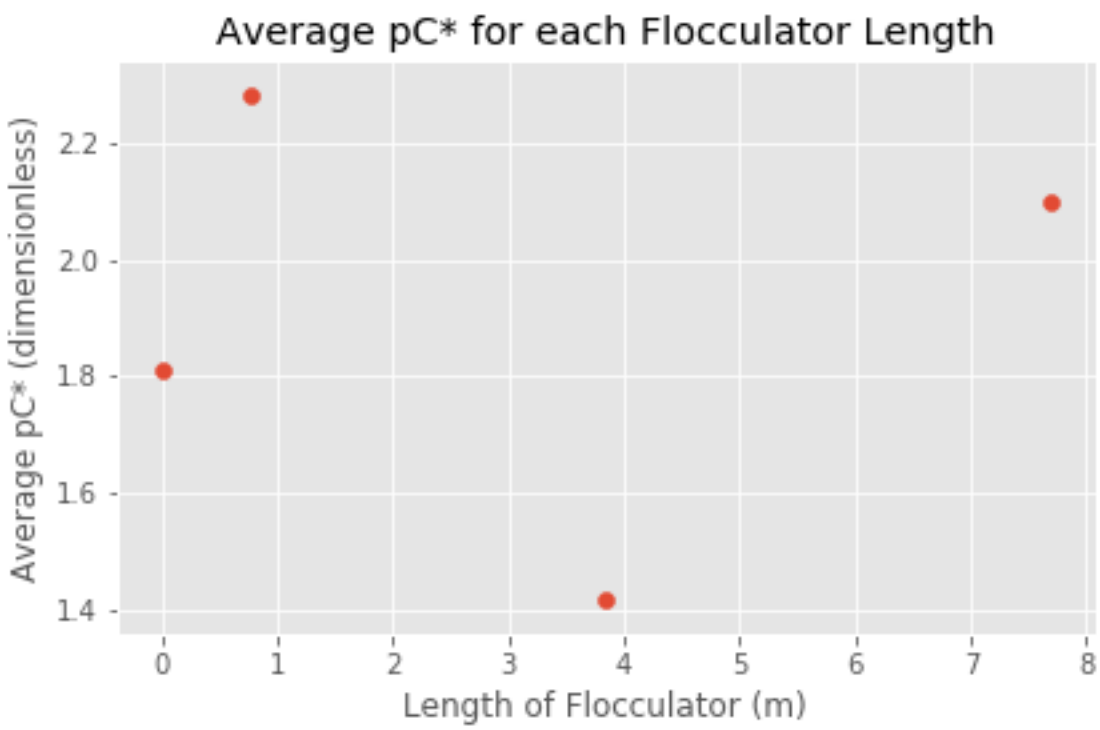

Figure 7: The average *pC* * for each flocculator length.

Discussion

From these experiments, there appears to be no correlation between flocculator length and filter performance. The team believes there are a few possibilities for the lack of a statistical difference between the flocculator lengths. First, since the team only effectively varied the residence time of the flocculator, the team just altered the collision potential ($G\theta$) of the flocculator. However, this does not necessarily allow for more successful collisions. It is theorized that if flocs grow too large, primary particles will not have the ability to successfully collide with them. Therefore, even if the team increased the number of chances these primary particles have to collide with flocs, if the flocs are too large, these primary particles will not successfully attach.

These experiments lead the team to hypothesize that the velocity gradient (G) is a much more important parameter in creating flocs than residence time (θ) and the collision potential ($G\theta$).

Conclusions

The team created a high shear flocculator and varied the residence time (θ) and collision potential ($G\theta$) to see if the team could effectively improve filter performance. The team hypothesized that this would decrease the number of primary particles that pass through the filter without being intercepted. However, this hypothesis was not supported by the experiments run by the team, since there was no correlation between the length of the flocculator and the performance of the sand filter. This leads the team to believe that varying the length of the flocculator is not an effective means to improve filter performance. Instead, other parameters such as the velocity gradient (G) should be tested to improve the performance of filters.

Comments and Suggestions

Some things that went well in our experiment were that we were able to set up a working experimental apparatus, we did not have any large messes or injuries, and we successfully gathered data that we could analyze. The data acquisition software was also sufficient for this experiment. A lot of things that did not go as well are addressed in the hurdles/challenges section above. One change we could make to our apparatus is to design a refilling stock tank, so we did not need to worry about running out of the water. Another improvement that could be made to the experimental apparatus is to add another pump for the coagulant and to add a flow accumulator to reduce pulsing. We also suggest that more research is done on this topic, particularly in regards to changing other parameters such as changing G instead of θ.

References

1 : Weber-Shirk, M. L., & Lion, L. W. (2010). Flocculation model and collision potential for reactors with flows characterized by high Peclet numbers. Water Research,44(18), 5180-5187. doi:10.1016/j.watres.2010.06.026

2 : Ovenden, C., & Xiao, H. (2002). Flocculation behaviour and mechanisms of cationic inorganic microparticle/polymer systems. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 197(1-3), 225-234. doi:10.1016/s0927-7757(01)00903-7

Appendix A: Python Code

Calculating G and θ

```
#finding the necessary length of flocculator
from aide_design.play import *
import aide_design.floc_model as flocm

V_filter = 1.85*u.mm/u.s
A_filter = np.pi*(25/2*u.mm)**2
Q_filter = V_filter*A_filter
Q_filter.to(u.mL/u.s)

id_tubing = 3/16*(u.inch)
radius_coil = 1.5*(u.inch)
temp = 22.3*(u.degC)

G = flocm.g_coil(Q_filter, id_tubing, radius_coil, temp)
varying_Gt = np.array([1000, 5000, 10000])
length = ((10000/G)*Q_filter)/pc.area_circle(id_tubing)
Gt = flocm.g_time_res(Q_filter, id_tubing, radius_coil, length, temp)

resonance_time = (pc.area_circle(id_tubing)*length)/(Q_filter)
print('The resonance time of the flocculator is ',resonance_time.to(u.minute),'.')

length.to(u.m)

print('Using',id_tubing,' length of tubing is ',length.to(u.m),
      'and the Gt value is',Gt,'.')
```

```
h_floc = 2.5*(u.m) #what we're aiming for
```

Apparatus Calculations

```
#Stock Solution Calculations
c_plant = 5*(u.NTU)
v_clay_stock = 3*(u.L)
M_clay = c_plant*v_clay_stock
print('Mass of clay needed for stock is',M_clay.to(u.mg),'.')

HA_stock_ratio = 0.118
M_HA = M_clay*HA_stock_ratio
print('Mass of humic acid needed is ',M_HA.to(u.mg),'.')

c_coag_tank = 50*(u.mg/u.L)
v_coag_tank = 1.0*(u.L)
c_coag_stock = 70.6*(u.g/u.L)

v_coag_stock = c_coag_tank*v_coag_tank/(c_coag_stock)
print('The coagulant added to stock tank is',v_coag_stock.to(u.mL),'.')

c_filter = 1.4*(u.mg/u.L) #THIS VALUE CAN CHANGE
Q_stock = Q_filter*c_filter/(c_coag_tank)
print('The flow rate of the stock tank is', Q_stock.to(u.mL/u.min),'.')

revolution_constant = 0.019*(u.mL/u.revolution) #orange-yellow tubing
RPM_pump = Q_stock/(revolution_constant)
print('The RPM of the coagulant pump is',RPM_pump.to(u.revolutions_per_minute),'.')
```

Graphing

```
from aide_design.play import *
from aguaclara_research import *
import Environmental_Processes_Analysis as EPA
import math

# File names
Firstfile = 'Final Project/ExcelFiles/datalog 5-7-2018.xls'
Secondfile = 'Final Project/ExcelFiles/datalog 5-8-2018.xls'

# Setting the start entries and end entries for each experiment
Firstfilerowstart = 10239
Firstfilerowend = 11446

NoFlocculatorstart = 104
NoFlocculatorend = 1303

Gtheta5000start = 1458
Gtheta5000end = 2655
```

```
Gtheta1000start = 3532
Gtheta1000end = 4672

# Used the Environmental Processes Analysis to create arrays of data for each experi
Gt_10000_Influent = EPA.Column_of_data(Firstfile,10239,11446,3,'NTU')
Gt_10000_Effluent = EPA.Column_of_data(Firstfile,10239,11446,2,'NTU')
Avg_10000_Influent = np.mean(Gt_10000_Influent[200:-1])
Avg_10000_Effluent = np.mean(Gt_10000_Effluent[200:-1])
time_10000 = EPA.ftime(Firstfile, 10239, 11446)
x_10000 = Gt_10000_Effluent/Gt_10000_Influent
pC_star_10000 = -1*np.log(x_10000)

ControlInfluent = EPA.Column_of_data(Secondfile,104,1303,3,'NTU')
ControlEffluent = EPA.Column_of_data(Secondfile,104,1303,2,'NTU')
Avg_ControlInfluent = np.mean(ControlInfluent[200:-1])
Avg_ControlEffluent = np.mean(ControlEffluent[200:-1])
time_control = EPA.ftime(Secondfile,104,1303)
x_control = ControlEffluent/ControlInfluent
pC_star_control = -np.log(x_control)

Gt5000Influent = EPA.Column_of_data(Secondfile,1458,2655,3,'NTU')
Gt5000Effluent = EPA.Column_of_data(Secondfile,1458,2655,2,'NTU')
Avg_5000Influent = np.mean(Gt5000Influent[200:-1])
Avg_5000Effluent = np.mean(Gt5000Effluent[200:-1])
time_5000 = EPA.ftime(Secondfile,1458,2655)
x_5000 = Gt5000Effluent/Gt5000Influent
pC_star_5000 = -np.log(x_5000)

Gt1000Influent = EPA.Column_of_data(Secondfile,3532,4672,3,'NTU')
Gt1000Effluent = EPA.Column_of_data(Secondfile,3532,4672,2,'NTU')
Avg_1000Influent = np.mean(Gt1000Influent[200:-1])
Avg_1000Effluent = np.mean(Gt1000Effluent[200:-1])
time_1000 = EPA.ftime(Secondfile,3532,4672)
x_1000 = Gt1000Effluent/Gt1000Influent
pC_star_1000 = -np.log(x_1000)

FlocAvgEffluent = np.array([Avg_ControlEffluent.magnitude,Avg_1000Effluent.magnitude

FlocAvgInfluent = np.array([Avg_ControlInfluent.magnitude,Avg_1000Influent.magnitude

FlocAvgInfluent
FlocAvgEffluent

FlocLength = np.array([0,0.768,3.84,7.683])

FlocAvgpC_star = -1*np.log(FlocAvgEffluent/FlocAvgInfluent)
FlocAvgpC_star
#pC_star = -np.log((effluent/influent).to_base_units()
```

```
plt.scatter(FlocLength,FlocAvgEffluent)
plt.title('Average Effluent for each Flocculator Length')
plt.xlabel('Length of Flocculator (m)')
plt.ylabel('Average Effluent Turbidity (NTU)')
plt.tight_layout()
plt.savefig('Final Project/Graphs/AvgEffluent_Flocculator.png')
plt.show()

plt.scatter(FlocLength,FlocAvgpC_star)
plt.title('Average pC* for each Flocculator Length')
plt.xlabel('Length of Flocculator (m)')
plt.ylabel('Average pC* (dimensionless)')
plt.tight_layout()
plt.savefig('Final Project/Graphs/Avg_pCstar.png')
plt.show()

plt.plot(time_10000.to(u.hour), Gt_10000_Influent, label = "Influent Turbidity")
plt.plot(time_10000.to(u.hour), Gt_10000_Effluent, label = "Effluent Turbidity")
plt.xlabel('Time (hr)')
plt.ylabel('Turbidity (NTU)')
plt.title('G\u03B8 = 10,000')
plt.legend()
plt.tight_layout()
plt.savefig('Final Project/Graphs/G_Theta_10000.png')
plt.show()

plt.plot(time_5000.to(u.hour), Gt5000Influent, label = "Influent Turbidity")
plt.plot(time_5000.to(u.hour), Gt5000Effluent, label = "Effluent Turbidity")
plt.xlabel('Time (hr)')
plt.ylabel('Turbidity (NTU)')
plt.title('G\u03B8 = 5,000')
plt.legend()
plt.tight_layout()
plt.savefig('Final Project/Graphs/G_Theta_5000.png')
plt.show()

plt.plot(time_1000.to(u.hour), Gt1000Influent, label = "Influent Turbidity")
plt.plot(time_1000.to(u.hour), Gt1000Effluent, label = "Effluent Turbidity")
plt.xlabel('Time (hr)')
plt.ylabel('Turbidity (NTU)')
plt.title('G\u03B8 = 1,000')
plt.legend()
plt.tight_layout()
plt.savefig('Final Project/Graphs/G_Theta_1000.png')
plt.show()

plt.plot(time_control.to(u.hour), ControlInfluent, label = "Influent Turbidity")
```

```python
plt.plot(time_control.to(u.hour), ControlEffluent, label = "Effluent Turbidity")
plt.xlabel('Time (hr)')
plt.ylabel('Turbidity (NTU)')
plt.title('Control Experiment Turbidity')
plt.legend()
plt.tight_layout()
plt.savefig('Final Project/Graphs/G_Theta_Control.png')
plt.show()

plt.plot(time_10000.to(u.hour), pC_star_10000, label = "G\u03B8 = 10,000")
plt.plot(time_5000.to(u.hour), pC_star_5000, label = "G\u03B8 = 5,000")
plt.plot(time_1000.to(u.hour), pC_star_1000, label = "G\u03B8 = 1,000")
plt.plot(time_control.to(u.hour), pC_star_control, label = "Control Experiment")
plt.title('pC* vs Time')
plt.xlabel('Time (hour)')
plt.ylabel('pC*')
plt.legend()
plt.tight_layout()
plt.savefig('Final Project/Graphs/pC_star.png')
plt.show()
```