Countercurrent Stacked Floc Blanket Reactor, Fall 2016

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December 13, 2016

Abstract

The countercurrent stacked floc blanket reactor is a system for removing suspended solids or dissolved dyes by coagulating them into larger lumps of particles referred to as flocs using opposing currents to run clean water one way and floc-ridden water the other way. Using two standardized reactors, dye and coagulant concentrations, and flow rates, the team worked towards determining whether multiple reactors in a series is more efficient than a single, long reactor. With the known mechanism and the result of previous research, this semester's goal was to intensify dye removal by modifying the design of the reactor, system flow path and flow rates. For the future, the flocculator will be modified to be longer allowing larger flocs to form, increasing efficiency of the system as a whole since the discrepancy in flocculator size prevented comparable performance between the single reactor system and the system of reactors in series.

Introduction

The countercurrent stacked floc blanket reactor (CSFBR) in combination with poly-aluminum chloride coagulant (PACl) has the potential to remove fluoride, arsenic and Remazol Brilliant Blue R dye (RBBR) from water with high efficiency; however, these flocs must then be removed in order to obtain clean water. Arsenic and fluoride are naturally occurring elements found in rock and soil that are toxic in their inorganic form. In many parts of the world, people are exposed to elevated levels of these contaminants through groundwater. Long-term exposure to arsenic and fluoride can lead to organ failure with internal hemorrhaging, and calcification of ligaments, respectively (Choubisa and Choubisa 2016). Presence of these inorganic contaminants in water, therefore, is a major health concern for communities around the world, especially in India. Another rising problem with water quality is textile dye contamination. Untreated dyes cause chemical and biological damage in aquatic systems, which threaten species of fish and aquatic plants. Furthermore, if untreated and ingested, synthetic dyes are known to be carcinogens and hormone disruptors.

The challenge of this team's project was to fabricate and test the dye removal efficiency of a two-reactor system with countercurrent flow. This system will then be compared against a similar system with only one reactor. Countercurrent flow is known to be an efficient way to remove particles from water by separating dirty flocs from clean water through the use of opposing and segregated currents. The idea is that floc blankets can fall down through the countercurrent flow due to their high density (in comparison with water). Extrapolating this idea to a system of reactors in series, flocs are driven back from one reactor to another. The hypothesis supported by the team is that the older flocs from a second reactor can improve the efficiency of the system by recycling the PACl and removing some dye of the dirty water in first reactor. Clean PACl will be used for the second reactor which will remove some dye as with a singular reactor system, but by recycling this used PACl to the first reactor, the first reactor can be more efficient by minimizing coagulant use. By completing this challenge, the team can contribute a significantly more efficient component of filtration to the AguaClara water filtration systems in India since coagulant consumption is directly related to the cost of running an AguaClara water filtration plant.

Literature Review

Coagulation

Many sources have shown that PACl seems to be the optimal coagulant for the purposes of the project which are to remove arsenic and fluoride from the water being treated (Zonoozi et al. 2009). PACl has been and continues to be used as the most common form of dye removal at the industrial scale. A main reason as to why PACl is so popular as opposed to other coagulants despite its cost is because PACl does not cause any leeching of hazardous chemicals into the water from dye decomposition (Golob et al. 2005). A drawback of PACl is that once its coagulation capabilities are saturated, the dye coagulation drops drastically while other coagulants are able to reach a maximum capacity and plateau. The team has been using PACl as the coagulant since the start of the project, thus for the sake of consistency in results, PACl will be used until the reactor design can be optimized. Only once the reactor is optimized can coagulant experimentation be considered.

Reactor Geometry

Last semester the CSFBR team noticed the sludge formation at some parts of the reactor. The team used opaque joints in the former reactors, thus it was impossible to figure out how the sludge formed at the joint. The handbook on hydraulic computation by the National Science Foundation showed data about the occurrence of local resistance at tubing joints. Figure 2 demonstrates the hydraulic properties of different angles of a joint and different flow rate ratios.

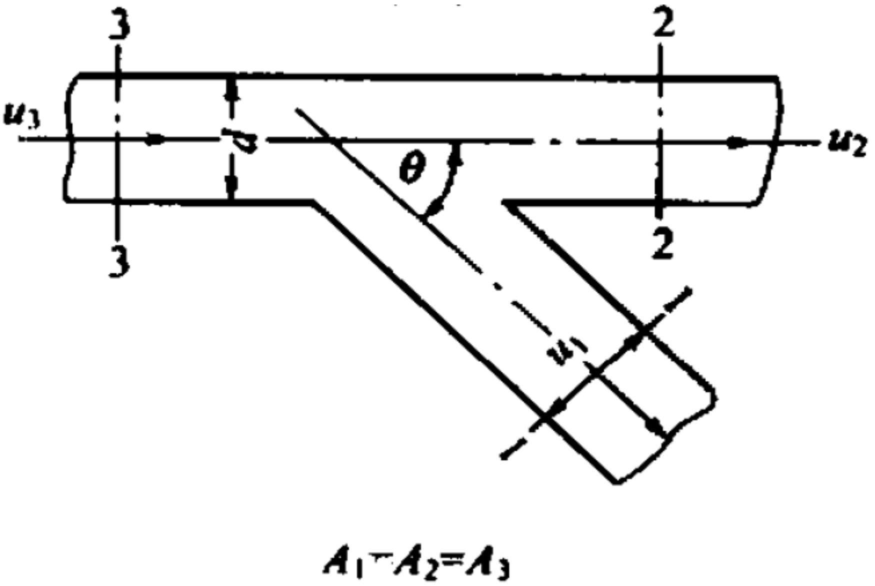


Figure 1: Diagram of a typical T-joint

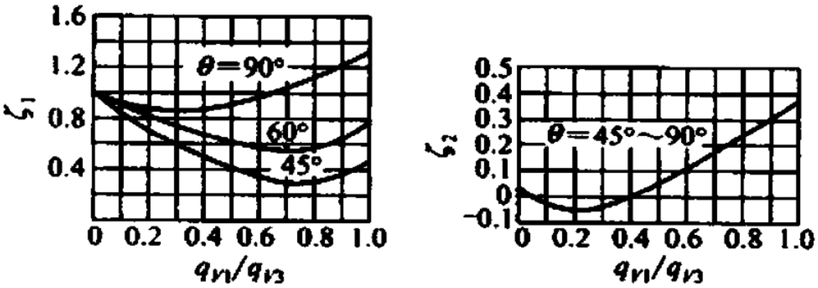
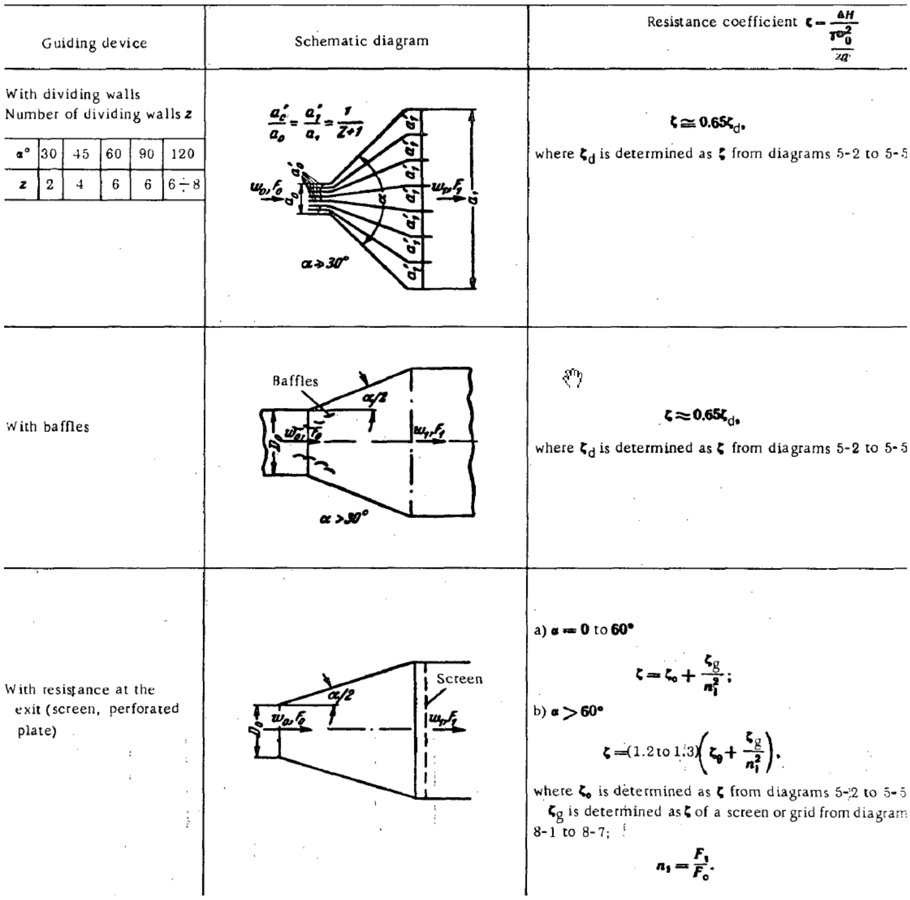


Figure 2: Graphs of joint-angle relation to flow rate (x-axis) and resistance coefficient (y-axis) from The National Science Foundation (1966)

According to figure 2, the angle of the joint relates greatly to the resistance. When the angle is 45°, the resistance coefficient has its lowest value. As the flow rate ratio of each pipe changes, the resistance of each pipe will change. We can adjust the resistance by changing the angle and the flow rate ratio to reduce sludge formation.

Another location where sludge formation was observed was the tube connection between the reactor and the flocculator at the bottom of the reactor. This connection can have differing shapes, which may affect sludge formation. The current design uses a diffuser-style connection where the connection begins with the radius of the tubing from the flocculator then gradually enlarges in a conical shape to match the radius of the reactor tube. A table by the National

Science Foundation shows the effect of diffuser geometry on flow and resistance. According to this table of the resistance of a short diffusive connection, the resistance changes as the structure of the connection or the radius of the tubing changes. Geometry of the connection insert can be modified to reduce the formation of the sludge.



Guiding device	Schematic diagram	Resistance coefficient $\zeta = \frac{\Delta H}{\frac{\gamma w_0^2}{2g}}$
With dividing walls Number of dividing walls z α°: 30, 45, 60, 90, 120 z: 2, 4, 6, 6, 6÷8	$\frac{a_0'}{a_0} = \frac{a_1'}{a_1} = \frac{1}{z+1}$; w_0, F_0; w_1, F_1; $\alpha > 30^\circ$	$\zeta \cong 0.65\zeta_d$, where ζ_d is determined as ζ from diagrams 5-2 to 5-5
With baffles	Baffles; $\alpha/2$; w_0, F_0; w_1, F_1; $\alpha > 30^\circ$	$\zeta \approx 0.65\zeta_d$, where ζ_d is determined as ζ from diagrams 5-2 to 5-5
With resistance at the exit (screen, perforated plate)	Screen; $\alpha/2$; w_0, F_0; w_1, F_1	a) $\alpha = 0$ to 60° $\zeta = \zeta_0 + \frac{\zeta_g}{n_1^2}$; b) $\alpha > 60^\circ$ $\zeta = (1.2 \text{ to } 1.3)\left(\zeta_0 + \frac{\zeta_g}{n_1^2}\right)$, where ζ_0 is determined as ζ from diagrams 5-2 to 5-5 ζ_g is determined as ζ of a screen or grid from diagram 8-1 to 8-7; $n_1 = \frac{F_1}{F_0}$.

Figure 3: Resistance of short diffusers with guiding devices or with resistance at the exit

Countercurrent Flow Theory

The use of countercurrent flow for separation of clean and dirty water is a major component of the CSFBR system. Countercurrent flow is a common concept that can be observed in biological systems such as the kidneys. Countercurrent parallel vessels exchange NaCl through passive diffusion to remove excess NaCl from fluid that would be then be circulated throughout the body (Kokko et al. 1972). A blood vessel runs alongside a vessel with the filtrate and the blood deposits water into an area of the kidney due to high salt concentration in that area, thereby decreasing salt concentration in the kidney. The parallel vessel with filtrate then diffuses salt into the same area as it flows in the opposite direction of the blood flow due to the difference in concentration gradient and completes the cycle of countercurrent exchange. The blood provides water and the filtrate provides the salt to the kidney to continuously drive the concentration gradient. Though in this case, the species to be decreased is salt concentration and in the case of the CSFBR flocs are meant to be removed, the theory behind the mechanism is the same as that used in the CSFBR system. The goal of the mechanism is to decrease the concentration of the species in a given volume by taking advantage of the path of the flow. In the CSFBR system, instead of diffusion, the weir is used to deposit flocs into the countercurrent. It is believed that this form of floc removal is most efficient and cost effective.

Previous Work

Spring 2016

ProCoDA Calibration

The spring 2016 CSFBR Team used ProCoDA, a data collection and system control software, for collecting and analyzing data. Since the photometer can only take voltage readings based on the amount of light that passes through the sample of effluent. ProCoDA takes these voltage readings, and calculates an absorbance based on the following relationship:

$$Absorbance = -log(\frac{V_(sample) - V_(dark)}{V_(blank) - V_(dark)})$$

Where Vsample is the voltage reading from the sample of effluent, Vblank is the voltage reading with clean tap water and Vdark is the voltage reading when the voltage sensor is completely covered. Once the absorbance is determined, ProCoDA converts absorbance to dye concentration,based on a calibration curve. The calibration curve was created by placing dye stock concentrations of 0,2,5,10,20,50,100$\frac{\text{mg}}{\text{L}}$ in the photometer, recording the respective voltage readings, and calculating the respective absorbance readings. Those absorbance readings were then plotted with their respective dye stock concentration. The calibration curve can be seen below in Figure 4.

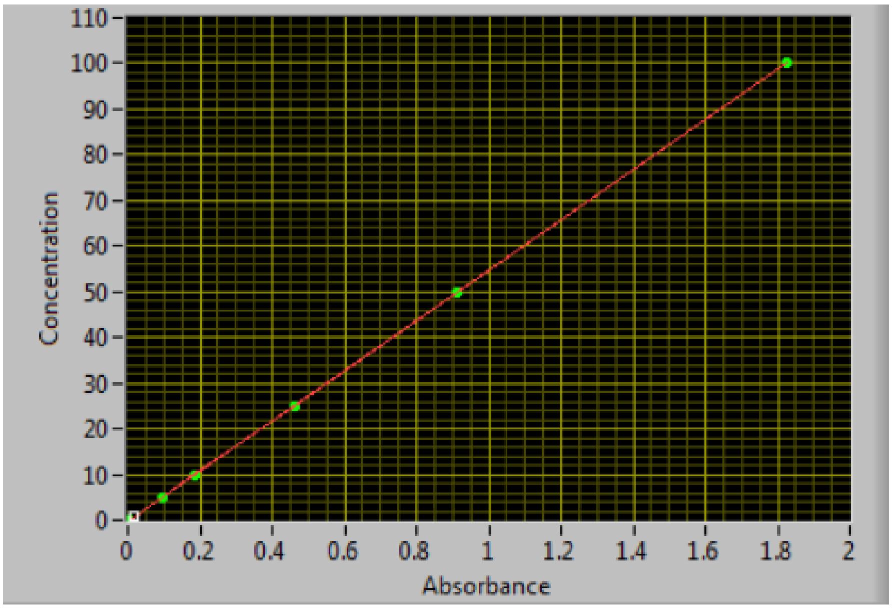


Figure 4: The calibration curve used by ProCoDA to linearly interpolate the relationship of dye concentration and absorbency.

Jar test

Jar tests were done in order to observe the adsorption relationship between the concentration of RBBR and the concentration of PACl, and the percent removal of dye from water. A summary of the jar test results can be seen in Figure 5.

Dye [mg/L]	PACl [mg/L]	t = 0 minutes	t = 15 minutes	t = 30 minutes	Top layer concentration [mg/L]	Percent Removal [%]
100	75	Dye added into stirred solution	Deep blue flocs formed. Top (mostly liquid) layer light blue	Very defined separation between liquid and floc layer. Liquid layer looks almost clear when extracting	5.56 mg/L	94.44
100	50	Dye added into stirred solution	Liquid layer is darker than previous trial. Floc formation evident but harder to see	Layers between settled flocs and liquid layer evident but not distinct. Liquid layer has blue tint when extracting	55.50 mg/L	44.5

Figure 5: Result from the jar test

Factor correction

To adjust for this error in the photometer's voltage readings, a correction factor was incorporated by the Spring 2016 Team. Figure 6 below shows a graphical representation of the results from the correction factor throughout their experiment. In the figure, the green line is the concentration of dye that was fed in. The red curve represents the raw data from the photometer, which has clay and

PACl interference. After applying the absorbance correction to the raw data, the blue curve was developed. This final blue line demonstrates dye removal from the influent feed.

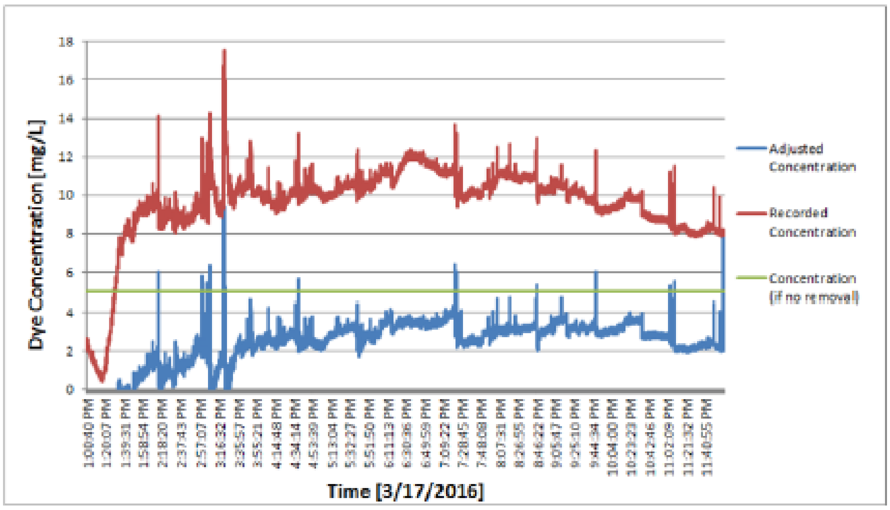


Figure 6: Graphical results illustrating the recorded concentrations of dye in the effluent with adjusted concentrations

Experiments

The Spring 2016 Team conducted several experiments with different parameters such as differing stock concentrations, and system running times. By adjusting the concentrations of PACl and dye, they increased the dye removal from 65.78% in the first experiment to 81.11% in the later experiment. Finally they determined the stock concentration of PACl to be $250 \frac{\text{mg}}{\text{L}}$ and the concentration of dye to be $5.00 \frac{\text{mg}}{\text{L}}$.

In Figure 7, the data from the last experiment of Spring 2016 Team has been graphed. The highest dye removal recorded was approximately 95.2%, but the lowest dye removal recorded was approximately 61.2%.

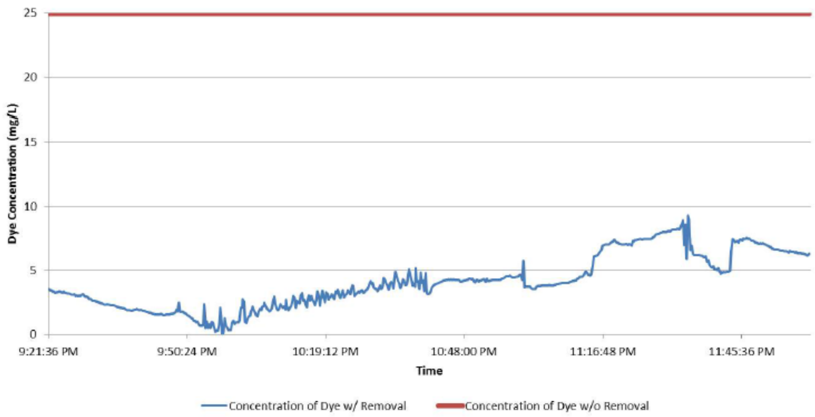


Figure 7: Graphical results from an over night run from April 25, 2016

As the experiment proceeded, the denser and heavier flocs in Reactor 3 were never re-suspended successfully because they settled in the bottom of the reactor near the jet whose velocity was not high enough to cause resuspension. This allowed for more flocs to settle, leading to sludge formation. Once the section of sludge reached about a third of the reactor's height, the flow of the system began pushing the plug up and out of the reactor and into the tube settler thereby increasing inefficiency of dye removal, as shown in Figure 7 starting just after 9:50PM. This led to the increasingly poor performance in the system. Due to the sludge formation, there was minimal transportation of flocs from Reactor 3 to Reactors 1 and 2, which prevented any conclusions from being made about whether multiple reactors in series would perform better than a single reactor.

Methods and Discussion

Fabrication of Reactors

Fabrication of the reactors and system was completed in the first part of the semester before testing began, this required making adjustments for better performance and data collection. The main change in construction was the transparent connection between different tubings that form the reactor. Instead of opaque joints, the team built a completely transparent reactor. The goal of this change was to be able to see what occurs in that crucial part of the reactor - the joint. Another relevant change from previous work was the adding of a settler tube (30-degree bend) so that small less dense flocs that escaped the floc blanket could settle and slide down along the tube before they reach the outlet of the reactor. Some other details the team considered was inverted cone shaped and smooth input. These efforts were all towards building reactors identical to the Fluoride team's in such a way that the two teams could reasonably compare results.

Table 1: Fabrication Specifications

Parameter	Value
Total reactor length	4 ft.
Vertical tube length	2 ft.
Settler tube length	2 ft.
Settler tube angle	30^o
Total weir tube length	8 in.
Weir height	21 in.
Weir tube angle	30^o
Reactor tubing diamenter	1.00 in.
Weir tubing diameter	0.50 in.
Flocculator tube length	32ft.

Materials

- Clear 1" PVC piping
- Clear 1/2" PVC piping
- Flexible and Hard 1/4" tubing

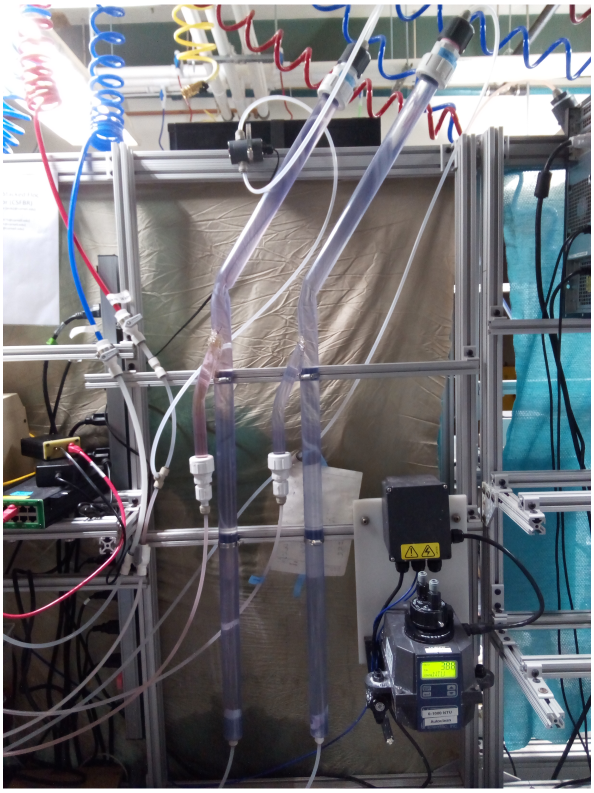


Figure 8: New identical reactors with 30-degree weir tube and 30-degree tube settler.

Set-up of the system

Once the reactors were built, the team was able to connect all the elements that take part in the whole system: reactors, the dye and tanks (with concentrations of 500$\frac{\text{mg}}{\text{L}}$ and 250$\frac{\text{mg}}{\text{L}}$, respectively), the flocculator to encourage floc formation by improving the mixing, three pumps (for tap water[1], waste water[2] and dye and coagulant[3]) and the photometer.

The pumps and photometers were then calibrated. For the calibration of the photometer, dye concentrations of 40, 20, 10, 5, 2.5, 1.25 and 0.625 $\frac{\text{mg}}{\text{L}}$ were used to simulate potential dye concentrations of clean water that would come out of the reactors. Multiple concentrations were used to ensure that the known input concentration would match the readings from the photometer. A linear relation between voltage and dye concentration analogous to that exhibited by the Spring 2015 team was obtained.

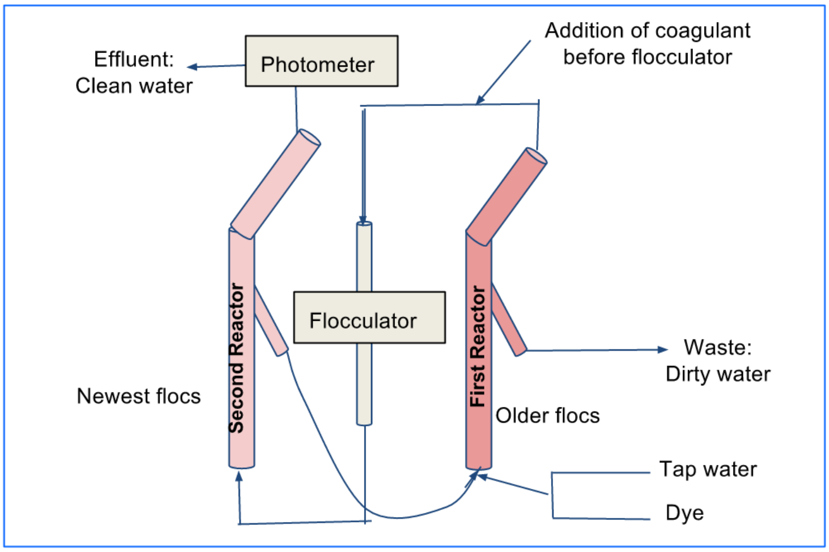


Figure 9: System schematic for use with two reactors.

As seen in Figure 9, tap water and dye enter in the system through the first reactor. At the beginning, this dirty water goes directly to the flocculator to be mixed with coagulant (PACl), then to the second reactor. This second reactor works as if there were only one reactor: recently formed flocs generate a dense floc blanket that deposits flocs through the countercurrent flow directed towards the first reactor (such that the used flocs are recycled into the first reactor). From this, the older flocs from the second reactor generate another floc blanket in the first reactor that fall down again through the countercurrent flow directed to waste water. On the other hand, water that comes up in the second reactor will exit the system after being analyzed by the photometer, that will provide numerical data of the concentration of clean water.

Materials

- Photometer

Table 2: Flow rates

Test condition	Water flow rate	Dye flow rate	PACl flow rate	Waste flow rate
1.0 $\frac{mm}{s}$, 50 $\frac{mg}{L}$ Dye	0.405 mL/s	0.051 mL/s	0.051 mL/s	0.135 mL/s
1.2 mm/s, 50 $\frac{mg}{L}$ Dye	0.486 mL/s	0.061 mL/s	0.061 mL/s	0.135 mL/s
1.4 mm/s, 50 $\frac{mg}{L}$ Dye	0.568 mL/s	0.071 mL/s	0.071 mL/s	0.135 mL/s
1.4 mm/s, 25 $\frac{mg}{L}$ Dye	0.638 mL/s	0.035 mL/s	0.035 mL/s	0.135 mL/s
1.5 mm/s, 50 $\frac{mg}{L}$ Dye	0.608 mL/s	0.076 mL/s	0.076 mL/s	0.135 mL/s
1.5 mm/s, 25 $\frac{mg}{L}$ Dye	0.684 mL/s	0.038 mL/s	0.038 mL/s	0.135 mL/s

- Polyaluminum Chloride (PACl)
- Red dye 40
- Various connectors and buckets for stocks
- Two 600 RPM Pumps and one 100 RPM
- Mechanical Stir and Stir plate with stir bar

Influent Concentrations

In order to be able to compare results between different systems, it is desirable to have visibly different effluent concentrations to be able to better compare the dye removal efficacy of the systems. One problem that was observed was that the PACl concentration was too high relative to that of the dye such that the steady state effluent concentrations were too low to be able to compare because the values were practically at their minimum. As a solution to this issue, ProCoDA and the stock concentrations were edited in such a way that a dye concentration in water of either 50 or 25 $\frac{mg}{L}$ was pumped through the reactors, with a corresponding PACl concentration yielding a dye-PACl ratio of 2:1. This ratio was chosen to obtain higher effluent concentrations so that the difference in effectiveness of two reactors against a single one would be more obvious. A compilation of the tested parameters are listed in table 2.

Upflow Velocities

As flow rates are key in the determination of system behavior, it was necessary to control and test them with minute differences. Regarding upflow velocity, the team tried to figure out the ideal one (high enough to avoid sludge formation at the bottom of the reactor and slow enough to allow flocs to settle down through the settler tube). Specifically, upflow velocities of 1, 1.2, 1.4 and 1.5 $\frac{mm}{s}$ were tested. A summary of these tests are shown in table 3.

Table 3: Behavior of upflow velocities

Upflow velocity	Result
$1.0 \frac{\mathrm{mm}}{\mathrm{s}}$	Sludge at the bottom of second reactor
$1.2 \frac{\mathrm{mm}}{\mathrm{s}}$	Sludge at the bottom of second reactor
$1.4 \frac{\mathrm{mm}}{\mathrm{s}}$	Accumulation of flocs at settler tube
$1.5 \frac{\mathrm{mm}}{\mathrm{s}}$	Accumulation of flocs at settler tube

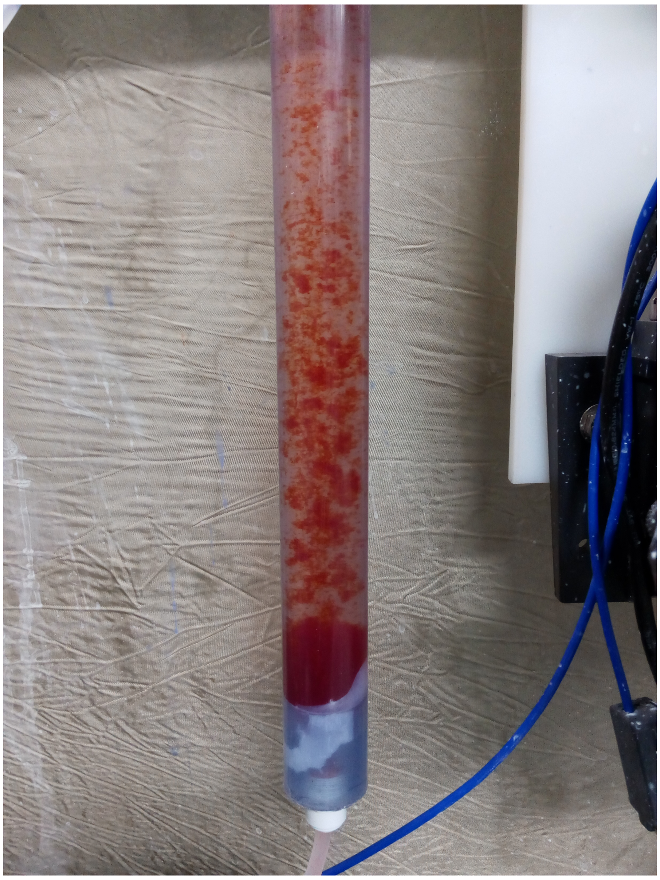


Figure 10: Sludge formation at the bottom of the second reactor (1 mm/s upflow velocity).

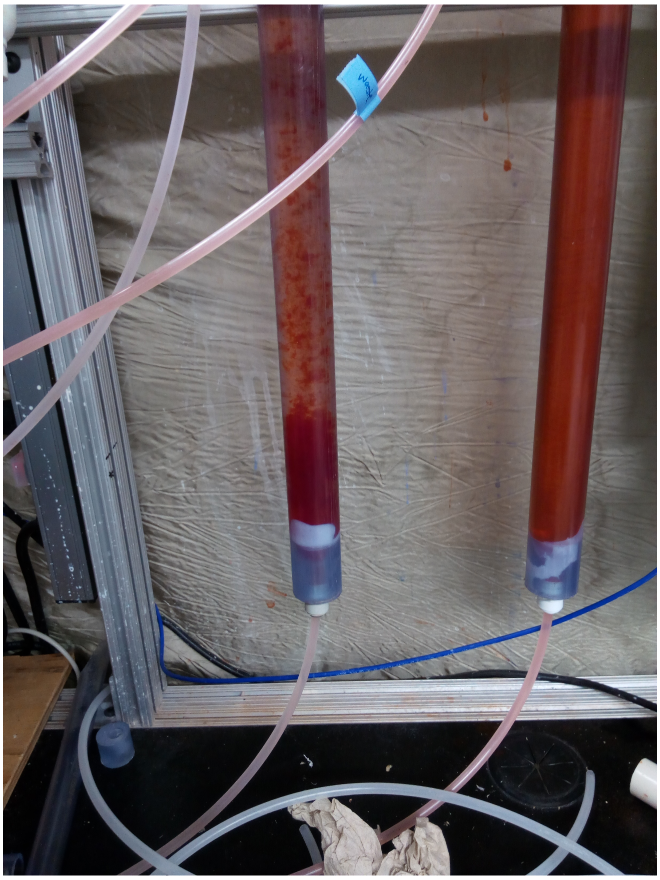


Figure 11: Sludge formation at the bottom of the second reactor (1.2mm/s upflow velocity).

The formation of sludge at the bottom of the reactors such as those seen in figures 10 and 11 made it impossible to obtain relevant data to be analyze the two-reactor system effectiveness. For this reason, the team directly decided against using the lower upflow velocities.

Figure 12: Floc blanket formation all along the second reactor (1.5mm/s upflow velocity).

Figure 13: Accummulation of flocs in settler tube of first reactor (1.5mm/s upflow velocity).

Utilization of either 1.4 or 1.5 $\frac{\text{mm}}{\text{s}}$ upflow velocity formed a dense floc blanket in the second reactor as seen in Figure 12 while some sludge accummulated in the first reactor settler tube, as shown in Figure 13. Observations point towards the high upflow velocity as the cause of this accumulation. The rapid stream seemed to push the flocs in the tube settler upwards, preventing them from settling down into the floc blanket and into the weir.

Weir Velocity

The desired weir flow rate should be at or below 10 percent of the upflow velocity in order to maximize the effluent floc-to-water ratio as not to waste any clean water. The 10 percent velocity was tested against a 20 percent weir velocity which is what the team had been using before to see if the target weir velocity was feasible. However, this 10 percent goal could not be achieved. The low velocity of 10 percent of the upflow velocity seemed to affect floc blanket formation negatively. Qualitative data suggested that the low weir velocity caused sludge formation, possibly due to low floc removal rate, resulting in more flocs being allowed to fall down the blanket, pushing it down to form sludge.

Results

During the semester, the team ran different experiments trying to obtain effluent concentrations which evinced that a two-reactor system worked better than a single reactor. The three main experiments run and their parameters are listed in table 4 below. The graphical time results of these tests are also shown in figures 14, 15, and 16.

Table 4: Test conditions and results

Date	11/15/16	11/28/16	11/29/16
Upflow Velocity	$1.5\frac{mm}{s}$	$1.5\frac{mm}{s}$	$1.4\frac{mm}{s}$
Dye Dosage	$50\ \frac{mg}{L}$	$25\ \frac{mg}{L}$	$50\ \frac{mg}{L}$
PACl Dosage	$25\ \frac{mg}{L}$	$12.5\ \frac{mg}{L}$	$25\ \frac{mg}{L}$
Test Duration	7 hr	23 hr	23 hr
Initial effluent concentration	$11\ \frac{mg}{L}$	$7\ \frac{mg}{L}$	$6\ \frac{mg}{L}$
Final effluent concentration	$13\ \frac{mg}{L}$	$17\frac{mg}{L}$	$13\ \frac{mg}{L}$
Percent removal average	77.37%	53.46%	82.95%

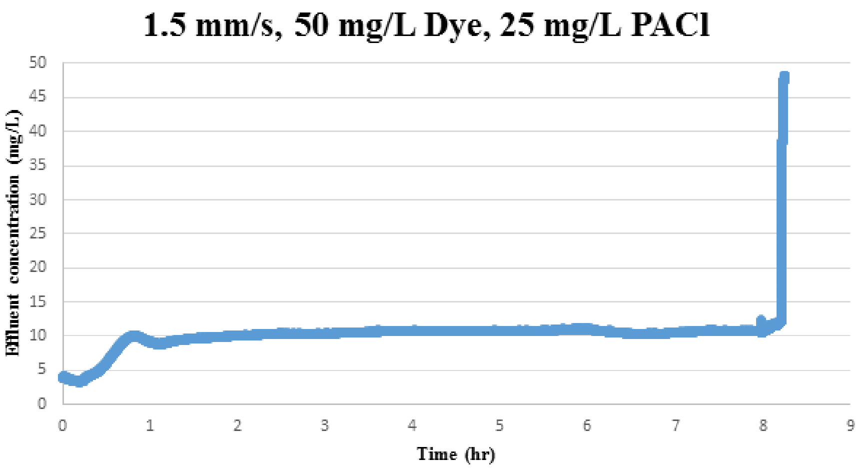


Figure 14: Effluent concentration from a test ran on November 15th, 2016 (1.5mm/s upflow velocity).

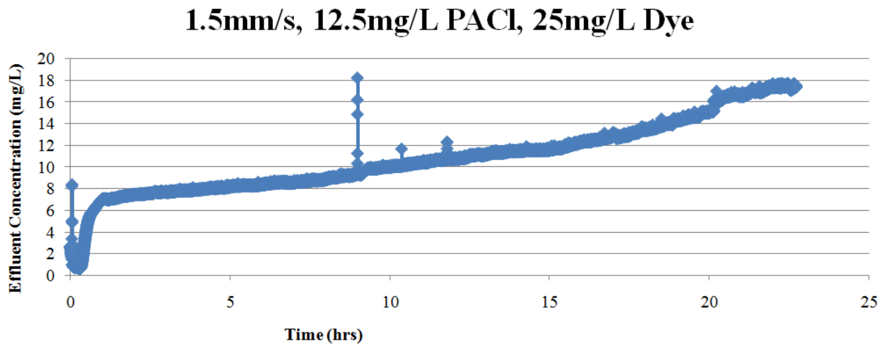


Figure 15: Effluent concentration from a test ran on November 28th, 2016 (1.5mm/s upflow velocity).

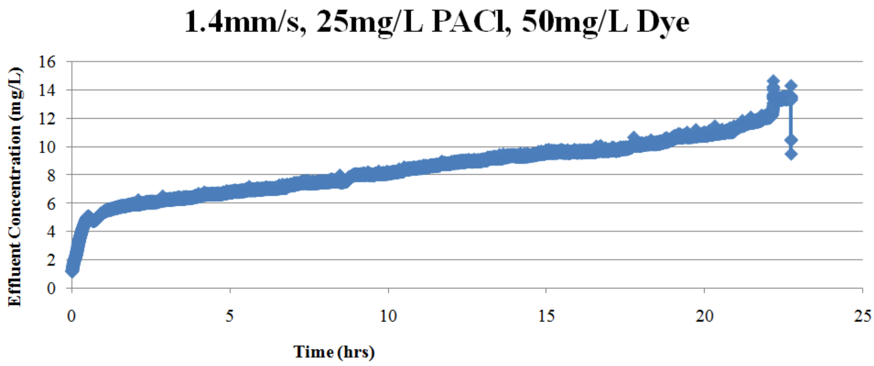


Figure 16: Effluent concentration from a test ran on November 29th, 2016 (1.4mm/s upflow velocity).

All three of the graphs of the results exhibited the same behavior in the beginning where the effluent concentration began very low and rapidly rose to a more steady effluent concentration as soon as the dye was added to the system. Only for the test at $1.5\frac{\text{mm}}{\text{s}}$ with $50\frac{\text{mg}}{\text{L}}$ dye was the effluent concentration completely constant through the test. The sudden jump at the end of the test is due to the depletion of coagulant in the middle of the test, which increased the effluent concentration to be the same as the influent concentration of $50\frac{\text{mg}}{\text{L}}$. This test had to be terminated after around 8 hours for this reason. The sudden jump at around 9 hours on the test at $1.5\frac{\text{mm}}{\text{s}}$ with $25\frac{\text{mg}}{\text{L}}$ of dye may be due to a one-time malfunction with the photometer where a bubble passed through. The drops in effluent concentration at the ends of the graphs were caused by the termination of the test where the photometer readings became inconsistent due to flow stoppage and system drainage.

Overall, the three experiments exhibited similar behavior throughout the tests. With the exception of the first test where the coagulant ran out, the team obtained consistent results. Even so, up until the termination point, the first test seemed to be performing similarly to the other tests. The second and third tests had dye concentrations that increased slowly but linearly. Just comparing the first 8 hours, it seemed that the first test would have performed similarly had it been able to be run for the full 24 hour duration.

Photometer Reading After the First Reactor

Once the team knew how the system works with a specific conditions, it was decided to replace the photometer right after the first reactor in such way that the removal of dye in the first reactor can be read and therefore, its efficiency can be checked. The unique test ran as described above was simulating the test already made on November 29th (see conditions above).

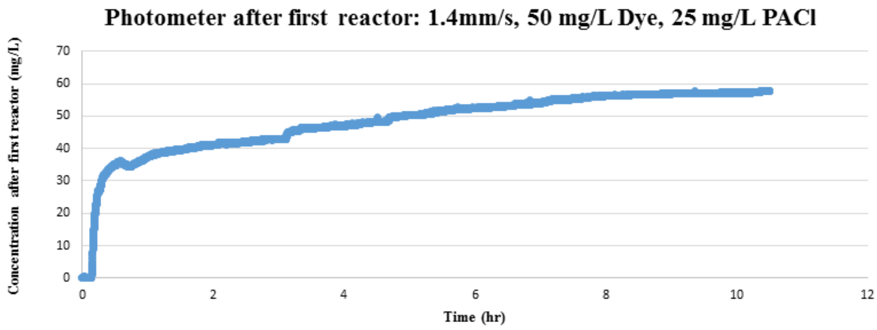


Figure 17: Concentration right after the first reactor to see first reactor efficiency (1.4mm/s upflow velocity).

Analysis

Upflow Velocity Effect On System Performance

Among all of the different experiments conducted during the semester, an unexpected observation that the team made was the vast effect of upflow velocity on the performance of the system. It has been already explained that low upflow velocities result in sludge formation at the bottom inlet of the reactors. However, beyond the velocity threshold at which sludge formation no longer occurs, lower velocities as close as possible to this threshold are preferred in order to minimize floc accumulation in the settling tube.

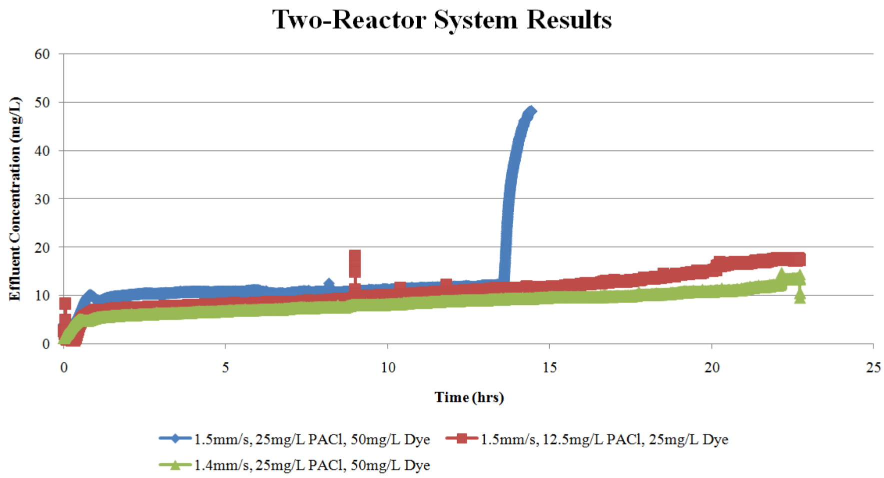


Figure 18: Overall comparison of tests. Lower effluent concentrations are obtained with lower upflow velocities.

As seen on figure 18 the lower upflow velocity resulted in a lower effluent concentration. Both upflow velocities ($1.4\frac{\text{mm}}{\text{s}}$ and $1.5\frac{\text{mm}}{\text{s}}$) had no sludge formation at the bottom. Flocs were able to fall down due to their density and the upflow velocity which propelled them proved to be crucial. The floc flow velocity near the weir needs to be as low as possible to allow floc descent into the weir to result in a more efficient countercurrent flow with a high floc-to-water ratio. This low velocity is also desirable at the settling tube to ensure that the small flocs that did not fall into the weir are caught in the settling tube. This would explain the lower effluent concentration obtained with the lower upflow velocity. Therefore, it can be concluded that lower upflow velocities are more efficient as long as velocity does not form sludge at the bottom of the reactors.

Sludge in Settler Tubes

Upon standardization of the reactor geometries with the fluoride team, CSFBR observed floc accumulation in the tube settlers resembling sludge. This kind of accumulatin was never observed with the fluoride reactors. Sludge formation in the settler tubes was one of the most relevant observations for the analysis of system performance. When the test was run, a significant accumulation of flocs was observed in the first reactor settler tube as shown in figure 19. This occurrence could be correlated to the quantitative data obtained from the same corresponding tests.

Figure 19: Sludge formation in first reactor settler tube (1.5 mm/s upflow velocity.

Concurrently, the effluent concentration also increased with time, as seen in figure 16. One of the proposed explanations for this phenomena was that sludge in the settler tube allowed dirtier water to pass through to the second reactor. This hypothesis was supported by the data from the photometer data in figure 17 where the concentration was measured after the first reactor. Consequently, water in the second reactor only became dirtier thus increased effluent concentration, under the assumption that the dye removal performance of the second reactor remained the same.

Similarly, the observed sludge formation may have been caused by the high upflow velocity. Although upflow velocity cannot be decreased too much in order to avoid sludge formation at the bottom of the reactor, it should be lowered to avoid floc movement beyond the settler tube.

The fluoride team also worked with the same reactor geometry and have observed no sludge formation in the settler tube when they used lower velocities and obtained consistent effluent concentrations as shown in the graph of figure 20. This discrepancy may have demonstrated that the reactors themselves were different between the two teams.

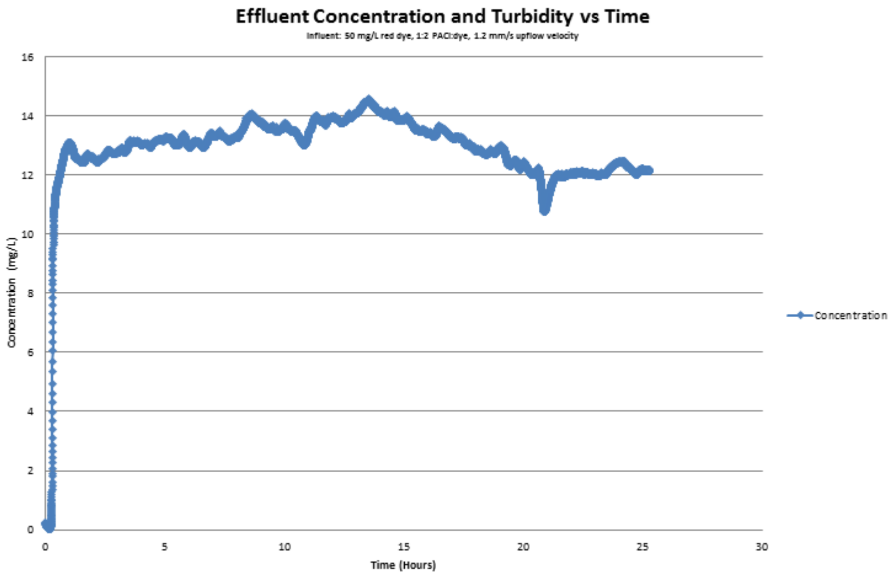


Figure 20: Consistent effluent concentration with 1.2 mm/s from Fluoride team

Single Reactor Versus Two-Reactor System

In the first comparison in Figure 21 , both tests were run with $1.5\frac{mm}{s}$, with a dye concentration of 50 $\frac{mg}{L}$ and a dye-PACl ratio of 2:1. A clear difference can be seen on the graph, with significantly cleaner water from two reactors. By using one reactor, effluent concentrations higher than 20 $\frac{mg}{L}$ were obtained, but there was a problem that occurred around the fifth hour with PACl stock that hindered the completion of a full 24-hour test. The same issue came up with the two-reactor system, but it gave results lower than 12 $\frac{mg}{L}$ until a problem with the PACl stock occurred around 8 hours into the experiment.

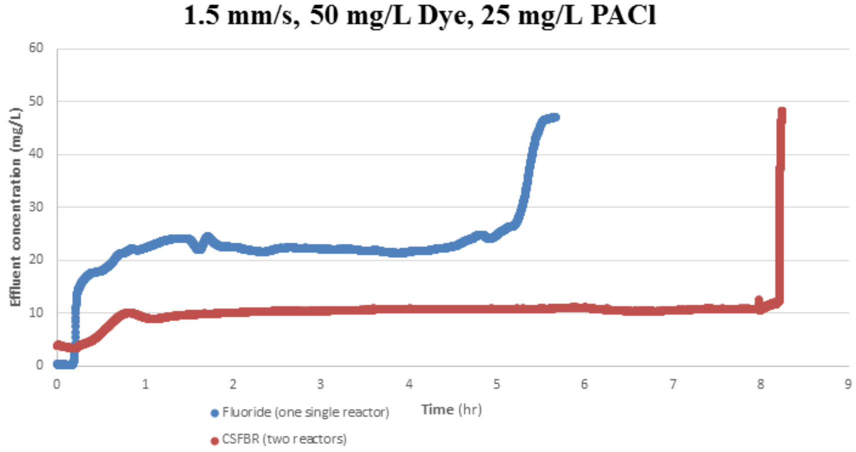


Figure 21: Effluent concentration of two-single reactor and one single reactor system at 1.5 mm/s upflow velocity, 25mg/L PACl, 50mg/L dye.

In the second comparison, shown in figure 22 , both tests were run with $1.5\frac{\text{mm}}{\text{s}}$, with a dye concentration of $25\frac{\text{mg}}{\text{L}}$ and a dye-PACl ratio of 2:1. In this experiment, the two systems gave very similar results. At the beginning, effluent concentrations were lower than $9\frac{\text{mg}}{\text{L}}$, while they increased to above $12.5\frac{\text{mg}}{\text{L}}$ after 24 hours. Although definitive conclusions about the two-reactor system efficiency cannot be drawn because of the similarity in results of the two systems, this comparison clearly shows the effluent concentration variance with time when the system is run with high upflow velocities.

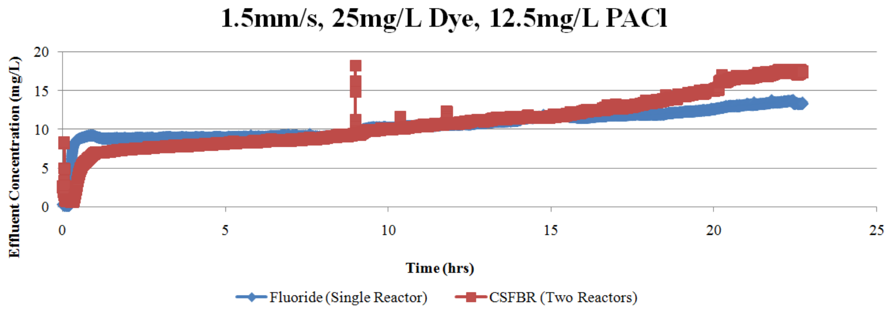


Figure 22: Effluent concentration of two-single reactor and one single reactor system at 1.5 mm/s upflow velocity, 12.5mg/L PACl, 25mg/L dye

In the third comparison, both tests were run at $1.4\frac{\text{mm}}{\text{s}}$, with a dye concentration of 50 $\frac{\text{mg}}{\text{L}}$ and a dye-PACl ratio of 2. In this case, it is difficult to make a logical comparison between the systems. The two-reactor system worked as expected (very low effluent concentration at the beginning and increasing effluent concentration throughout the 24 hours), while unexpected and inconsistent results were seen from the single reactor system suggesting that something went wrong half way through the test.

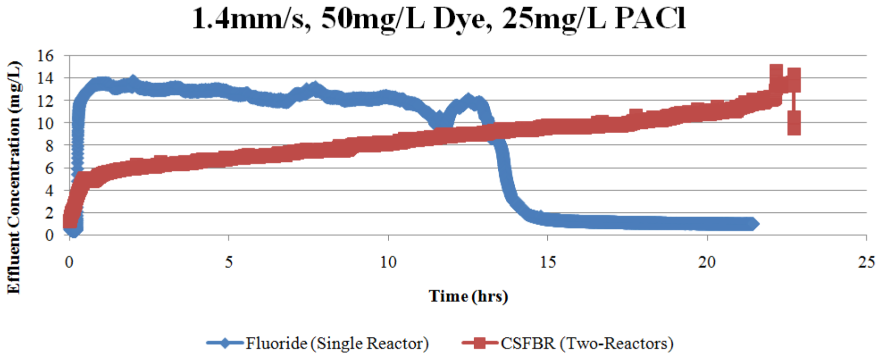


Figure 23: Effluent concentration of two-single reactor and one single reactor system at 1.4 mm/s upflow velocity, 25mg/L PACl, 50mg/L dye

Conclusions

Two-reactor system

The goal of CSFBR team was to determine whether or not a two-reactor system is more efficient against a single reactor system. After analysis and comparison of the results above, the team could not conclude for certain which system works better. Depending on the test conditions, the results between both systems were either very similar or slightly favorable to the two-reactor system.

One of the inconsistencies of most of the results was that effluent concentration did not remain constant over time. As explained earlier, this may have been due to the sludge formation in the first reactor settler tube. The high upflow velocity posed a problem because flocs were not able to fall down. As upflow velocity could not be decreased in the current system to avoid sludge formation at the bottom of the reactors, a possible factor that contributed to the inconsistency was improper fabrication of the inlet . A small defect in the drilling of the hole for the inlet may cause a deviation of the upflow jet that prevens it from propelling flocs all along the cross section of the reactor and consequently, allowed the settlement of flocs at the bottom.

Inlet shape change

Though it was hypothesized that the main reason for sludge formation at the bottom of the reactor lied in the inability of the jetstream to propel large, dense flocs that fall down, there may have been other contributing factors to sludge formation. When the upflow velocity was very low, it could not produce enough turbulence to create an ascendant flow of large flocs along the reactor and consequently, the floc blanket did not reach the countercurrent weir but instead, settled down to the bottom of the reactor forming a dense sludge layer. This phenomena can be seen above in Figure 10. The team considered changing the inlet shape in order to obtain a more homogeneous ascendant flow all along the reactor (mainly at the bottom), so that flocs could not settle down, forming sludge. The new inlet design consists of deforming a 1-inch diameter transparent tubing to create a narrow rectangle at the bottom that is then cut at a 60 degree slope.

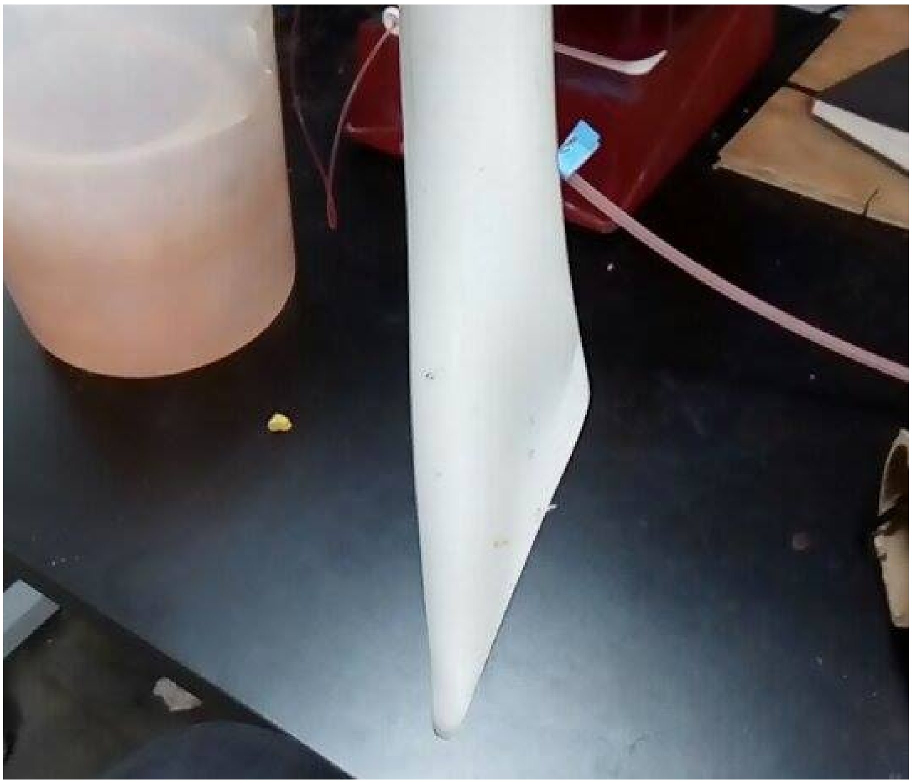


Figure 24: Model for the new inlet shape proposed for next semester.

Figure 25: Model for the new inlet shape proposed for next semester.

Stock concentration

Comparing results with the fluoride team demonstrated that higher dye concentrations allow for bigger differences in results between the two teams. In the case that one of the systems was more efficient than the other one, it would have been easier to compare that difference. Thusly, a dye concentration of $50\frac{\text{mg}}{\text{L}}$ and PACl concentration of $25\frac{\text{mg}}{\text{L}}$ were chosen be used.

Future Work

By working in parallel with the fluoride team, CSFBR will determine the necessity of two reactors in a system in comparison to just one. One inconsistency of the system to be addressed is the flocculator length. Previously, the two teams were unable to compare results due to differences in reactor construct (fluoride team had tube settlers and a longer reactor while CSFBR did not); however, upon standardizing the reactors, it became apparrent that another difference was the inlet shape of the reactors of each team. All possible differences should be avoided in order to be able to have further comparable results.

Another challenge that both CSFBR and Fluoride team should carry out is to change the inlet shape as it has been explained above, so that the upflow velocity can be moved down to 1 $\frac{\text{mm}}{\text{s}}$ but also a more realistic and homogeneous flow can propel flocs upwards.

Upon complete standardization of methods between the fluoride team and CSFBR (e.x. using the same stock PACl and dye concentrations), comparable results are expected to be obtained. Should the multiple reactors in series prove to perform significantly better than a single reactor, CSFBR will have to modify the system to suit the needs of AguaClara plants in India.

References

Efficiency of the coagulation/flocculation method for the treatment of dyebath effluents. Retrieved September 22, 2016 http://www.sciencedirect.com/ science/article/pii/S0143720804002724

Zonoozi, M. H., Moghaddam, R. A., Arami, M. (n.d.). Coagulation/flocculation of dye-containing solutions using polyaluminium chloride and alum.

Esparza, M. (n.d.). U.S. Patent No. US 6,461,535 B1. Washington, DC: U.S. Patent and Trademark Office.

Choubisa, S. L. and Choubisa, D. (2016). Status of industrial fluoride pollution and its diverse adverse health effects in man and domestic animals in India.Environmental Science and Pollution Research International, 23(8):72447254.

Kokko, J. P., Rector, F. C. (1972). Countercurrent multiplication system without active transport in inner medulla. Kidney International, 2(4), 214–223. doi:10.1038/ki.1972.97

Semester Schedule

Task Map

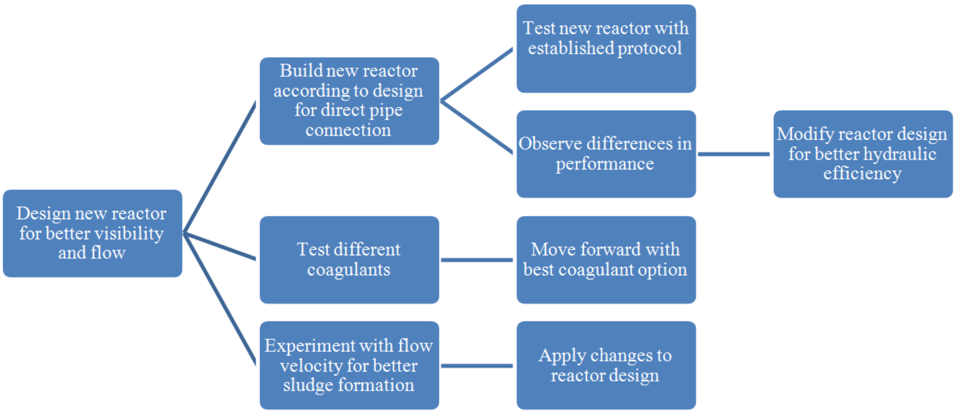


Figure 26: Task Map

Task List

1. Develop a new reactor (9/14/16) - Jacqueline Dokko
   Use the basic shape of the old reactor but with clear tubing such that activity can be observed throughout the reactor. Go to machine shop to build the designed reactor.

2. Build flocculator (9/19/16) - Javier Espada
   Use the Mathcad code from the Fluoride team flocculator to calculate necessary radius and flexible tubing length to build desired flocculator.

3. Put together entire system (9/21/16) - Jacqueline Dokko
   Be in touch with former members to attain advice on putting together the system. Look to fluoride team's system as an example.

4. Test new reactors (9/30/16) - Javier Espada
   Upon building the entire system, begin running it to test for any leaks or other problems. Observe the behavior of the new reactors to compare to old reactor performance.

5. Modify system for better flow (10/5/16) - Javier Espada
   Identify characteristics of the reactor which could be improved and design a new reactor or other parts of the system. Said changes will be applied and tested.

6. Test different flow velocities (10/22/16) - Jacqueline Dokko
   Experiment with different reactor positioning to see how gravitational flow would affect the flow and sludge formation.

Report Proofreader: Jacqueline Dokko