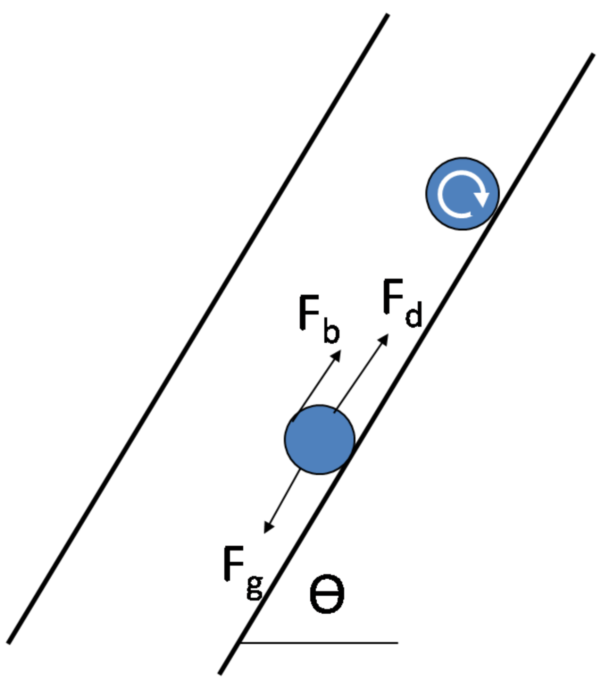
PSS Experiments with the Velocity Gradient

Created by Alexander Campbell Duncan, last modified by Rachel Beth Philipson on Dec 07, 2009

Abstract

The Plate Settler Spacing team is currently investigating the Floc Roll-Up Phenomenon in the tube settler. By developing a velocity gradient model, we hope to both analytically and experimentally determine the critical velocity floc particles experience when they begin to roll up the settler tube and into the effluent rather than settling back down the tube and into the floc blanket. The critical velocity is determined using a force balance for a floc particle. In addition to determining this critical velocity, we hope to understand how properties of the flocs themselves affect floc roll-up.

Overview of Methods



When fluid flows through a cylindrical tube its velocity relative to the walls changes as a function of the tube radius. In general, this velocity distribution is parabolic: the greatest velocities are achieved at the center of the tube (where R=0) eventually tapering off to 0 at the walls. The parabolic nature of the distribution arises from cylindrical symmetry and that the fluid does not move at the walls (the "no-slip" condition).

This gradient in the velocity profile contributes to the force that a floc rolling up the edge experiences, it creates a drag force acting on the edge of the particle closest to the center of the tube, which is one of three forces included in the force balance on the particle. In smaller diameter tubes, the velocity gradient will have a greater slope increasing the local velocity a particle of the same size will experience on the side closest to the center of the tube. This discrepency between the no slip condition at the wall and the velocity experienced on the side closest to the center of the tube in some cases may be great enough to cause floc roll-up.

Flocs actually begin to roll up when the forces that would cause a floc particle to move up into the effluent exceed the gravity force that sends the floc particle back to the floc blanket. The velocity experienced by the floc particles at the point at which they begin to roll up the tube rather than settle out is called the critical velocity. The settling velocity of a floc particle is dependent on floc diameter and floc density. Conversely, the critical velocity a floc experiences is dependent on floc diameter and the inner tube diameter.

Theoretical Analysis of the Velocity Gradient

Ramp State Experiment

Theoretical Analysis of the Velocity Gradient

Created by Zachary N Romeo, last modified by Rachel Beth Philipson on Dec 09, 2009

Theoretical Analysis of the Velocity Gradient

This analysis was for both a tube and plate settler. Although tube settlers are used in the lab, plate settlers are used in the Honduras plants. Therefore, a model that takes into account the differences between the two apparatuses must be developed. With an accurate way to model floc roll up in a tube or plate settler, we can predict when floc roll up will happen given a set of conditions. This can help us optimize the plate settler spacing in order to prevent floc roll up from occuring.

Laminar Flow Profile

Calculation of Ratio of Settling Velocity to Particle Velocity

Plate Settler Spacing

Recommendations

*More detail on the calculation process outlined above can be found in the Math CAD File

No labels

PSS Velocity Gradient Theory Laminar Flow Profile

Created by Rachel Beth Philipson, last modified on Dec 09, 2009

Laminar Flow Profile

One design constraint is to ensure that the flow is laminar. Turbulent flow cannot be modeled analytically and thus we would not be able to reliably predict plate settler performance.

The entrance region was checked to ensure that the parabolic velocity profile was fully established. This was done by calculating the distance that it will take laminar flow to become fully developed. This entrance region length is compared to the length of the tube settler, and if the ratio is less than one, then laminar flow is fully developed

The entrance regions are always less than the length of the plate settlers (Figure 7).

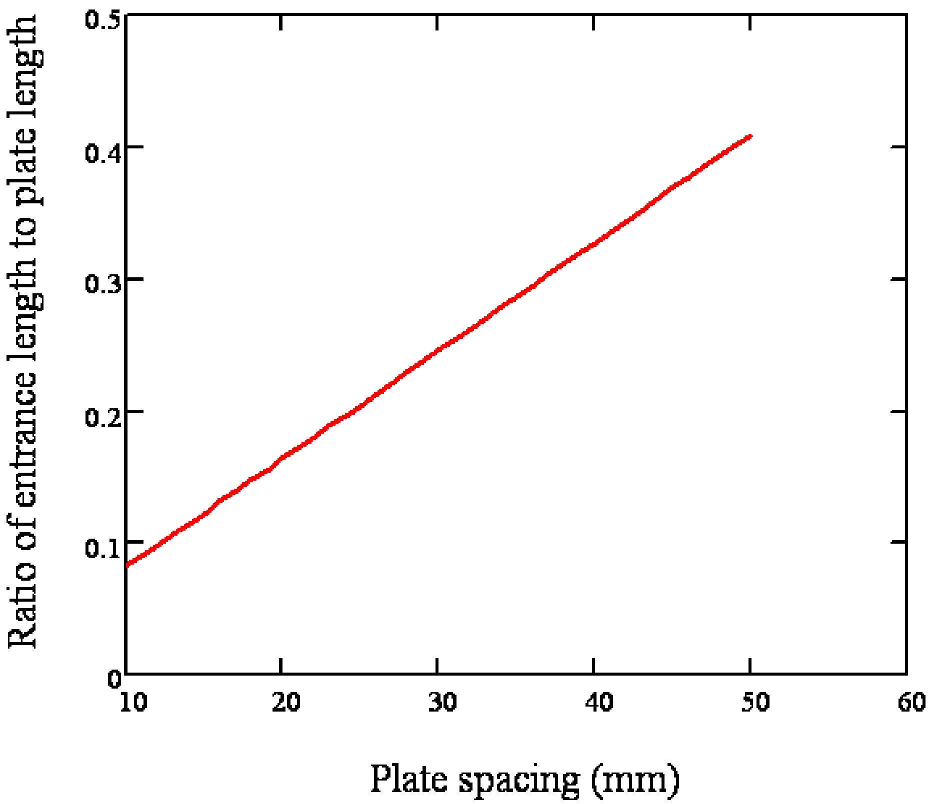


Figure 7: Entrance Region vs. Plate Settler Spacing

No labels

PSS Velocity Gradient Theory Settling Velocity Particle Velocity Ratio

Created by Rachel Beth Philipson, last modified on Dec 07, 2009

Calculation of Ratio of Settling Velocity to Particle Velocity

The calculation of this ratio is very important in order to begin modeling floc roll up. This ratio is the key to determining whether or not floc roll up will occur for a given set of conditions. In order to determine the critical velocity at which floc particles will begin to roll up the tube and into the effluent, we compare the settling velocity with the particle velocity experienced from the velocity gradient.

The settling velocity of a particle in a tube settler can be expressed as follows (Munson, 1998)

$$V_t = \frac{g d_0^{(3-D_{Fractal})} d^{(D_{Fractal}-1)}}{18\Phi\nu}\left(\frac{\rho_{Floc_0}}{\rho_{H_2O}} - 1\right)$$

Where:

g = Gravity

d_o

= size of the primary particles

$D_{fractal}$

= fractal dimension of the floc particles

Φ

= shape factor for drag on flocs which is equal to

ν

= viscosity

ρ_{floc}

= density of the floc particle

ρ_{H_2O}

= density of water

The particle velocity experienced as a result of the velocity gradient can be expressed as follows (Munson, 1998)

$$V_{particle} = V_{ratio} V_\alpha \left[1 - \left(\frac{\frac{d_{tube}}{2} - d_{Floc}}{\frac{d_{Tube}}{2}}\right)^2\right]$$

Where

V_α

= directional velocity in the tube settler

d_{tube}

= diameter of the tube settler

d_{floc}

= the diameter of floc particles

Vratio = the maximum velocity at the center of the tube- for a plate settler this value is 1.5 times the average velocity. For a tube settler this value is 2.

Therefore, the ratio between the settling velocity of the particle and the velocity experienced as a result of the velocity gradient can be expressed as by the below equation.

$$\Pi_V = \frac{\frac{g\sin(\alpha)d_0^2}{18\Phi\nu}\frac{\rho_{Floc_0}-\rho_{H_2O}}{\rho_{H_2O}}\left(\frac{d_{Floc}}{d_0}\right)^{D_{Fractal}-1}}{V_{ratio}\frac{V_{Up}}{\sin(\alpha)}\left[1-\left(\frac{\frac{d_{Tube}}{2}-d_{Floc}}{\frac{d_{Tube}}{2}}\right)^2\right]}$$

This ratio is a function of particle diameter, tube diameter, upflow velocity and the angle of the plate settler. When this ratio is greater than one (ie the settling velocity is greater than the velocity experienced by the floc particles in the tube), the flocs will fall back into floc blanket. When this ratio is equal to one, the particles will remain stationary in the tube settler. When the ratio is less than one, the velocity of the particles will exceed the settling velocity and the floc particles will roll up into the effluent, creating a highter turbidity.

References

Munson, B.,Young, D., Okiishi, T., (1998). *Fundamentals of Fluid Mechanics* (3rd ed.). New York, NY: John Wiley & Sons, Inc.

No labels

PSS Velocity Gradient Theory Plate Settler Spacing

Created by Rachel Beth Philipson, last modified on Dec 09, 2009

Plate Settler Spacing

Figure 1 shows the floc size that could be captured by different tube settler diameters. When the ratio has a value of 1, the sedimentation velocity matches the upflow velocity of the floc particle, and this is defined as the critical diameter, i.e. the floc diameter in which floc roll up will begin, for each of the given tube diameters and plate settler spacing.

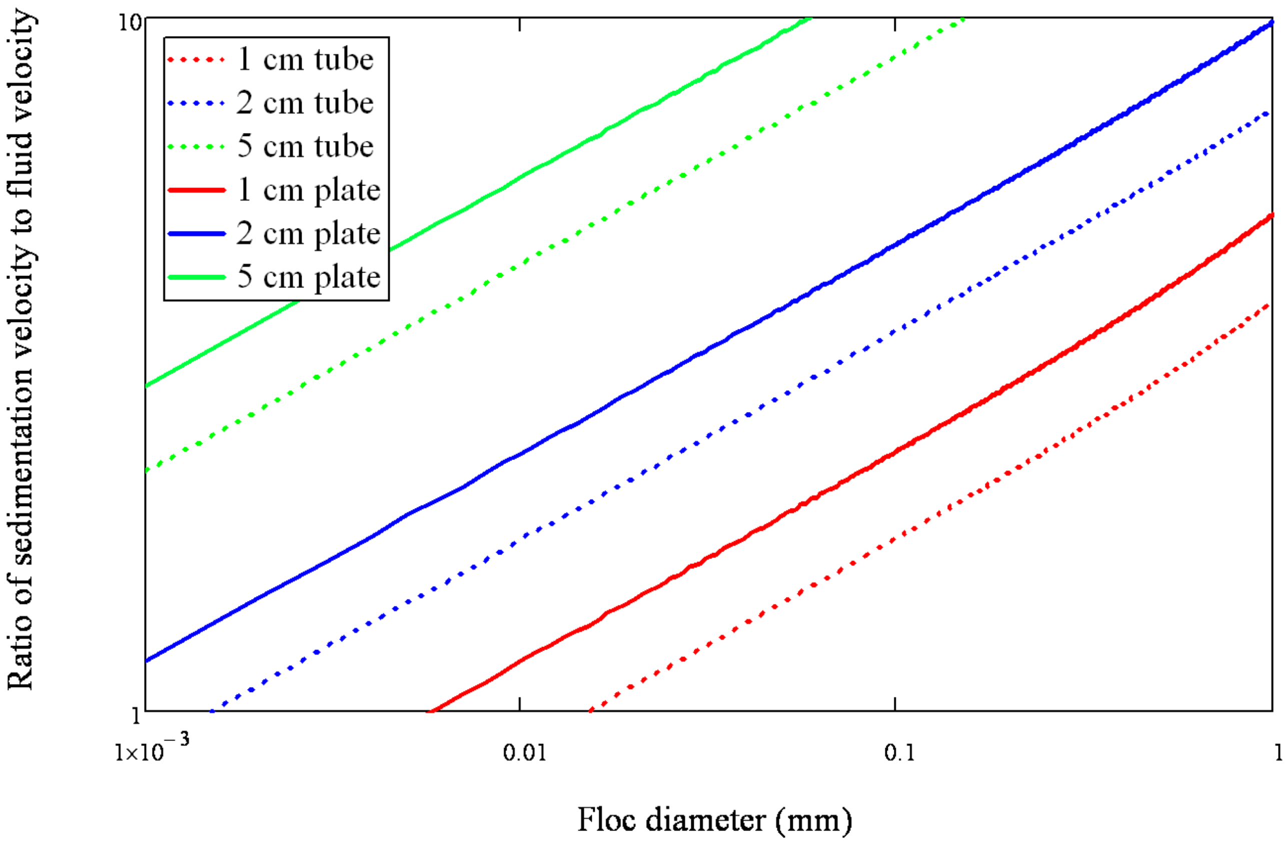


Figure 1: The ratio of Sedimentation Velocity to Fluid Velocity vs. Floc Diameter

The graph is cut off at a particle size of 1 mm that is on the order of magnitude of size of a colloidal particle. For plate spacings greater than or equal to 2 cm and for tube diameters greater than or equal to 5 cm, it is predicted that there will be no floc roll up under AguaClara conditions.

Calculation of the Minimum Diameter of the Flocs that Settle from the Sedimentation Velocity Equation

Assuming an upward flow velocity of 1.2 mm/s, which used in the newer AguaClara plants, the diameter of floc that will roll-up was determined by using a root finding algorithm, and the plate settler spacing or tube diameter was plotted versus the minimum floc diameter. The minimum floc diameter corresponds to the minimum size of a floc particle that will roll up into the effluent; or the maximum size of a floc particle that the plate settler will prevent from going into the effluent.

!Plate spacing vs floc diameter.png\|width=700px,align=centre!

Figure 2: Plate Spacing or Tube Diameter vs. Minimum Floc Diameter

The minimum floc diameter corresponds to the minimum size of particles that will still settle out of the tube and return to the floc blanket instead of going into the effluent. With larger plate settler spacing, most floc roll-up could theroetically be eliminated.

The minimum floc diameter that will be captured for a given upflow velocity and tube settler diameter can be calculated in the equation below. This equation uses a simplification that the velocity profile is linear, not parabolic, near the wall. This linearized approach produces very similiar results (Perhaps statistically quantify this with some sample diameters.

Figure 3 graphically displays the linear velocity gradient solutions. The curves are not quite straight on a log log plot. This is due to the quadratic in the velocity profile. We can obtain a very good approximation by using the velocity gradient at the wall and assuming a linear velocity gradient. That assumption makes an analytical solution possible.

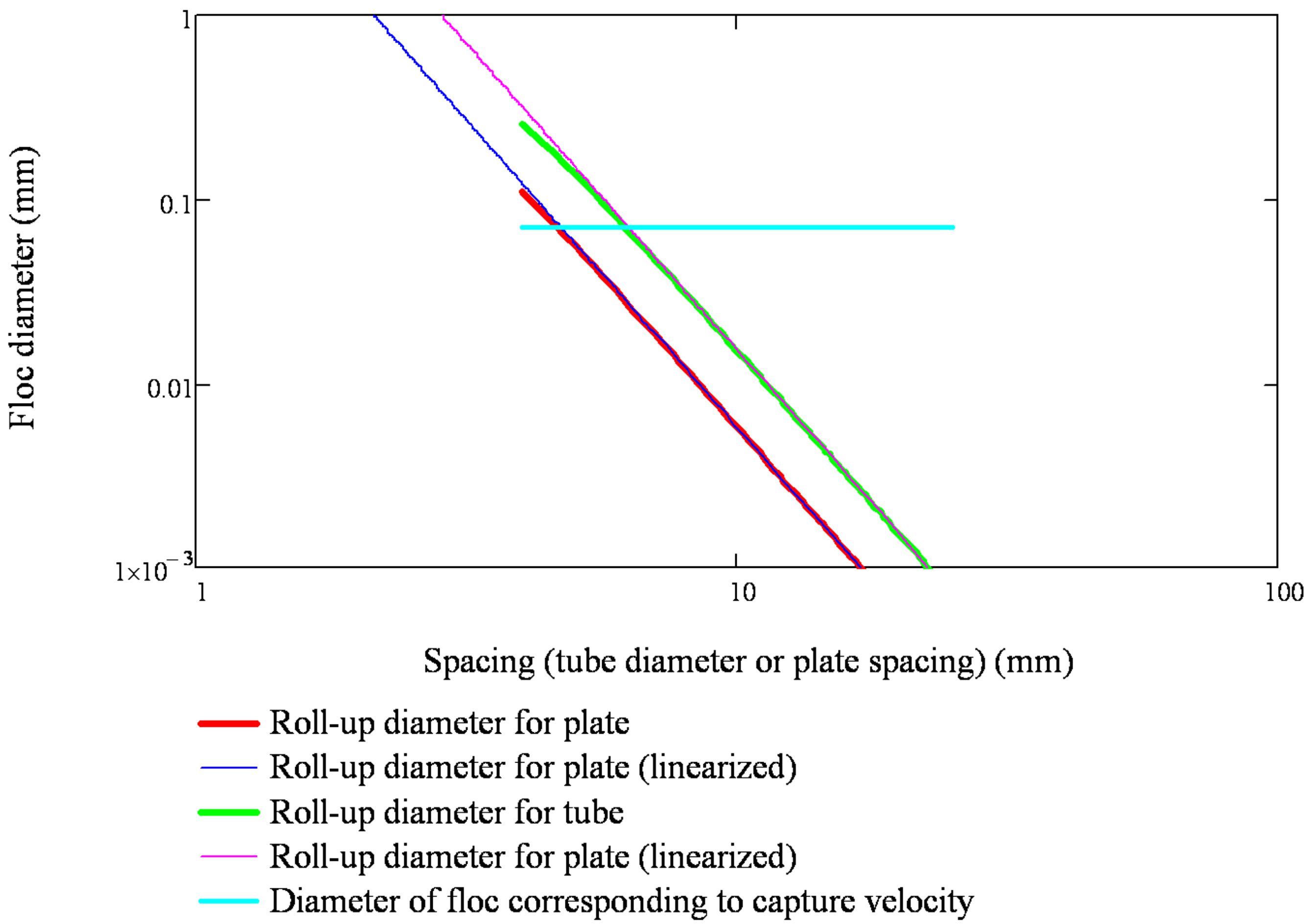


Figure 3: Floc Diameter vs. Spacing

For small floc sizes this linearization is valid and produces an analytical solution. For larger flocs that could roll-up, the linearization is invalid because the slope tends more and more parabolic closer the the center. However, Figure 4 illustrates that linearized equations show that with smaller tubes, the size of a floc particle that will roll up into the effluent varies very little with vertical velocity.

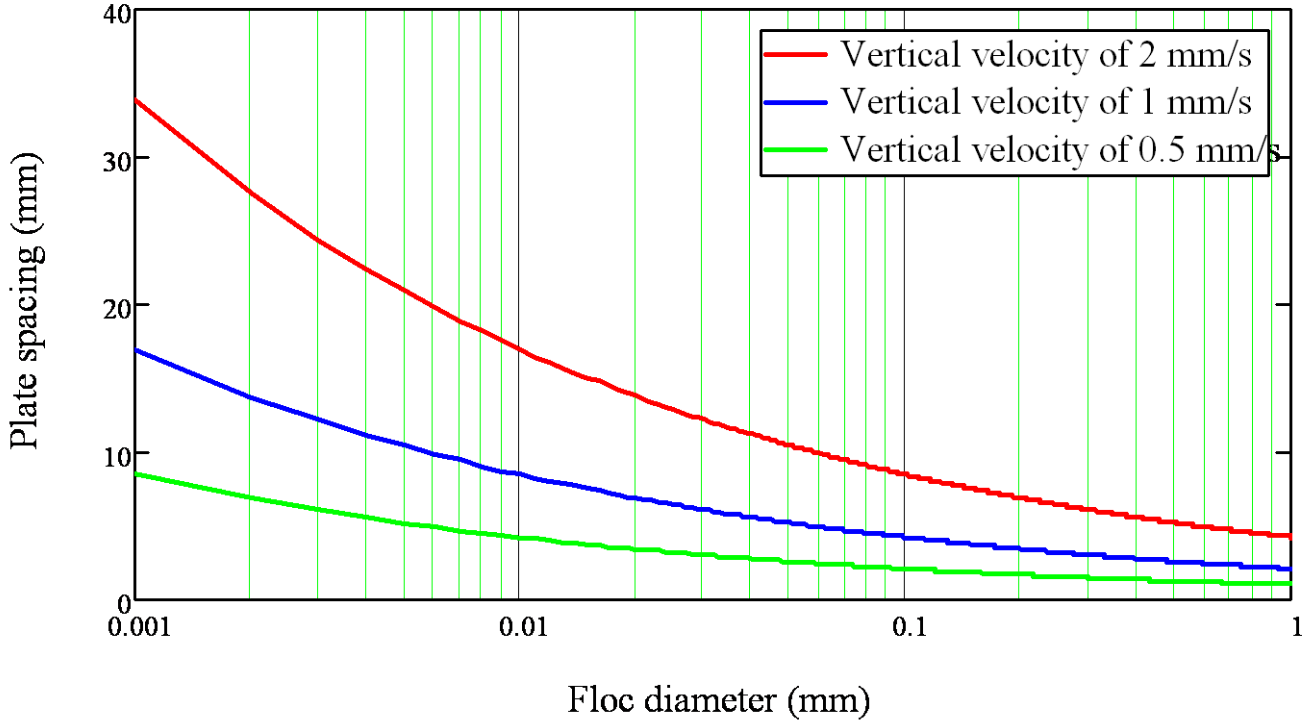


Figure 4: Floc Spacing vs. Floc Diameter

$$d = d_0 \left(\frac{18 V_t \Phi \nu_{H_2O}}{g d_0^2} \frac{\rho_{H_2O}}{\rho_{Floc_0} - \rho_{H_2O}} \right)^{\frac{1}{D_{Fractal} - 1}}$$

The critical velocity model can be utilized to calculate the desired spacing to capture a floc particle of a particular size. The following equation results were summarized in Figure 5. Figure 5 represents the minimum spacing that will capture a floc particle with a particular settling velocity.

$$S = V_{up} \frac{108 \Phi \nu_{H_2O} d^2}{g \sin^2(\alpha) d_0^3} \left(\frac{d_0}{d} \right)^{D_{Fractal}} \frac{\rho_{H_2O}}{\rho_{Floc_0} - \rho_{H_2O}}$$

Where:
$alpha$

= The angle of the tube settler (60 degrees)

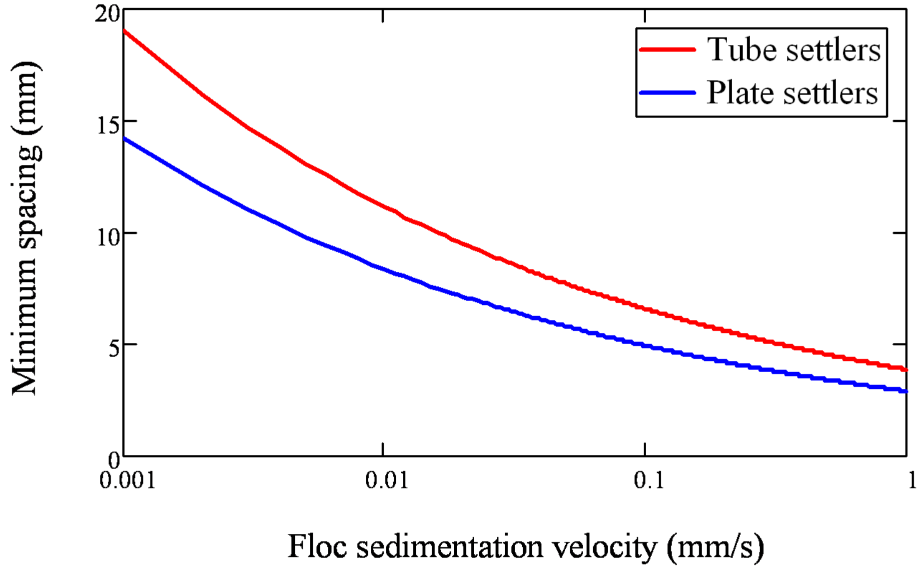


Figure 5: Minimum spacing vs. Floc Sedimentation Velocity

Figure 6 represents the absolute minimum plate settler spacing that will capture floc particles with a settling velocity of 0.12 mm/s in an AguaClara plant. Theoretically, any spacing below the intersection of two lines would produce a worsened effluent turbidity.

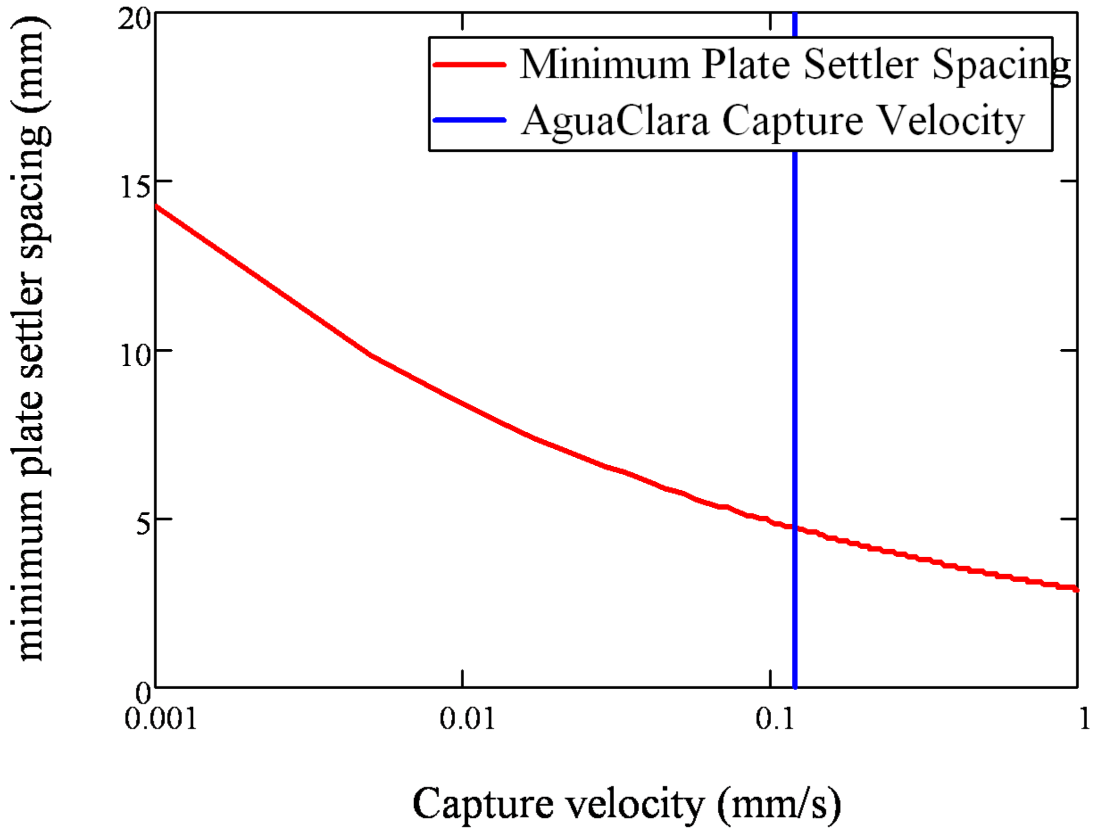


Figure 6: Minimum Plate Settler Spacing vs. Capture Velocity

No labels

If you have a disability and are having trouble accessing information on this website or need materials in an alternate format, contact web-

PSS Velocity Gradient Theory Recommendations

Created by Rachel Beth Philipson, last modified on Dec 07, 2009

Recommendations

Based on the calculations associated with the critical velocity theory, the best way to avoid floc roll up is to maximize the plate settler spacing. Figure 1 shows the minimum plate settler spacing that will produce acceptable results. From the graph, it can be estimated that this diameter is approximately 5 mm. On the graph, this is the intersection of the minimum plate settler spacing that will produce acceptable performance and the specified AguaClara capture velocity.

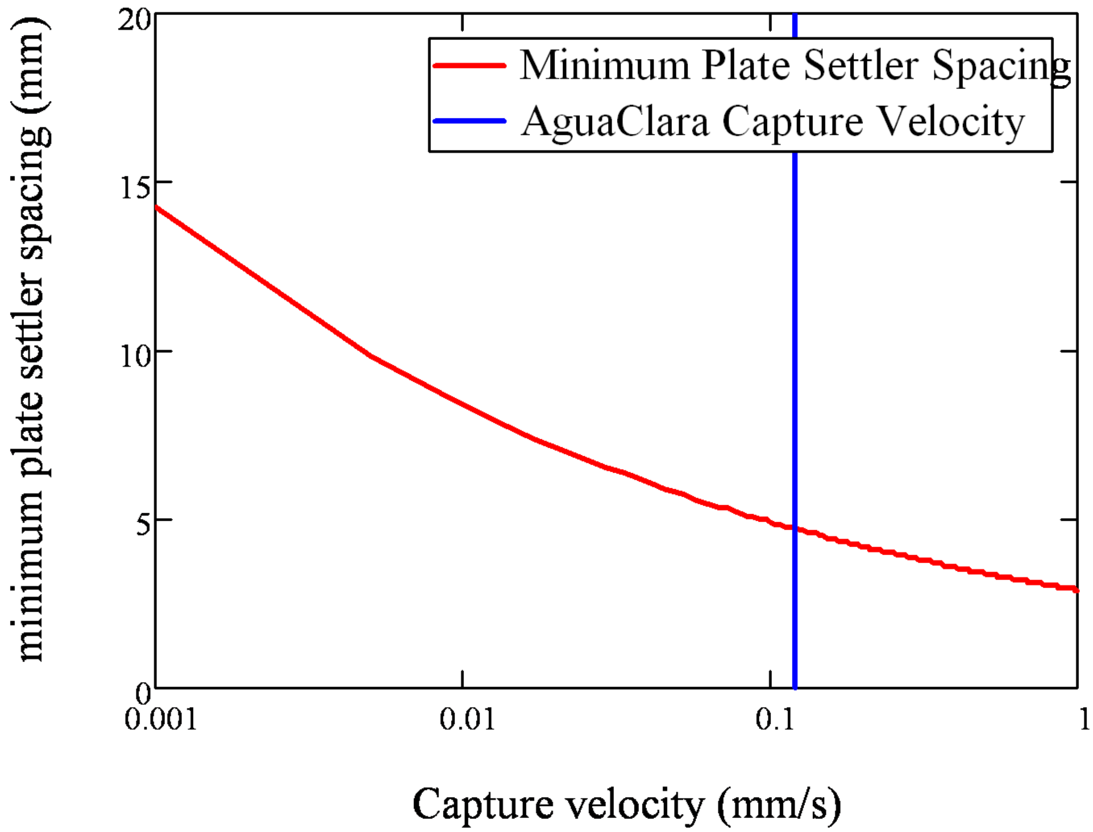


Figure 1: Minimum Plate Settler Spacing vs. Capture Velocity

Figure 2 illustrates the minimum particle size that will roll up the plate settler plotted against plate settler spacing. The line at the order of magnitude of colloidal particle size shows that at a plate settler spacing of approximately 17 mm and a tube diameter of 23 mm there should theoretically be no floc roll up.

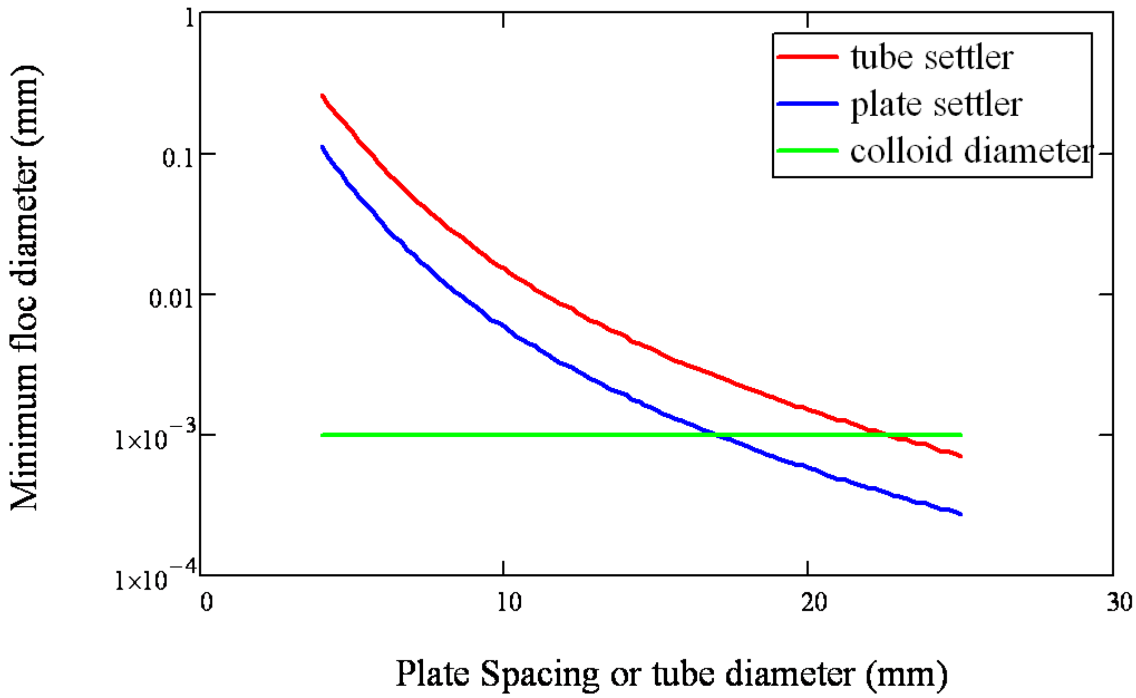


Figure 2: Plate Settler Spacing vs. Floc Diameter

Although the critical velocity theory suggests that larger plate settler spacing will produce the best results, the capture velocity theory suggests that failure will occurs with a larger plate settler spacing. Theoretically, at different terminal velocities (which can be converted to a particle diameter) either the capture velocity theory or the critical velocity

By comparing the size of floc particles that both the critical velocity theory and the capture velocity theory should theoretically filter out of the effluent, you can see which theory should govern the plate settler behavior. The equations relating the critical and capture velocity are as follows:

$$Q_{critical} = \frac{\pi S V \sin\theta^2}{32 d_0^2 \left[\frac{-18 V \Phi \nu \rho_{H2O}}{d_0^2 g(\rho_{H2O} - \rho_{Floc})}\right]^{\frac{1}{D_{Fractal}-1}}}$$

$$Q_{capture} = \frac{L\cos\theta + S\sin\theta}{S}\left[\pi\left(\frac{S}{2}\right)^2\right] V$$

Where

S = Tube settler diameter (or spacing)
d0 = size of primary particles
V = Predicted Terminal Velocity
Φ

= Shape Factor

Since, with our experiments, all of these variables will be held constant except for the spacing, we can analyze these relationships between critical and capture velocity theories for different tube diameters. The predicted terminal settling velocity is a range from 5 to 100 meters per day. For each spacing, this is what is varied in order to get a range of flow rates to be tested in each ramp state experiment.

Figure 3 shows the difference between the 6.35 mm tube and the 23.8 mm tube in terms of what size particles the settler will prevent from going into the effluent. Roll-up will dominate effluent performance for these settling velocity ranges in 6.35 mm tube compared to 23.8 mm tube.

For the 23.8mm tube, the capture velocity theory governs the size of particles that settle out. Ramp State experiments are being done to confirm this. This goes along with the theory that there should be minimal to no floc roll up for tube settlers with larger diameters. If the capture velocity is governing the floc particles that end up in the effluent, then any floc roll up in the plate settler must be insignificant compared to the number of floc particles that the plate settler is not capturing.

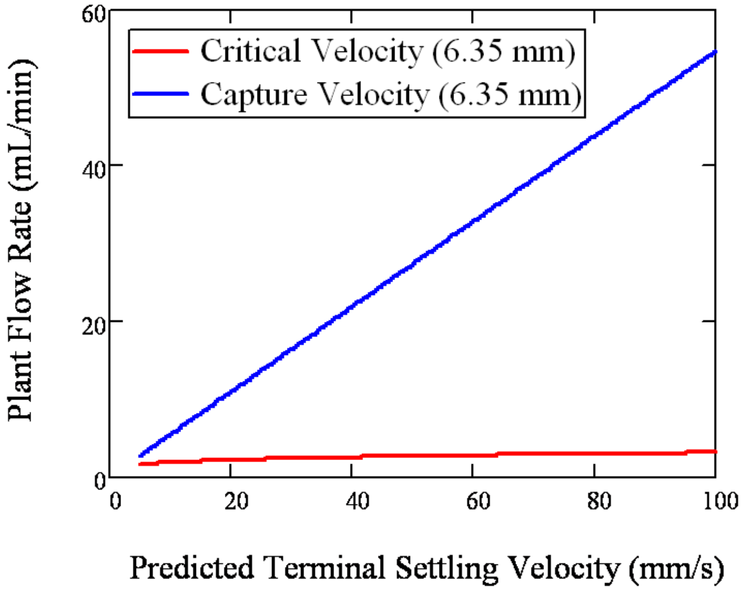
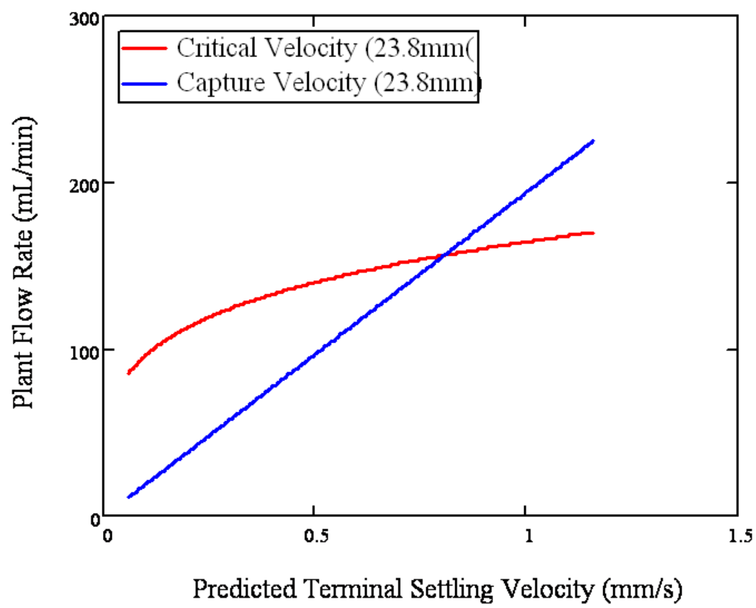


Figure 3: Plant Flow Rate vs. Terminal Velocity (Particle Size) for 6.35 mm tube and 23.8 mm tube

Based on this analysis, a larger tube would be more effective because the minimum size of particles that are settled out is larger. However, this theory needs to be tested, so the Ramp State Experiments are being run to try to match up experimental data to this theory.



No labels

2 Comments

Matthew William Hurst

This page is a great idea. It should be re-structured so that more explanation is being done and less putting in image in and explaining around the image in text. Your images should support your text, not the other way around.

Anonymous

t

PSS Fall 2009 Ramp State Experiment

Created by Rachel Beth Philipson, last modified by Elizabeth Hope Tutunjian on Dec 07, 2009

Overview of Methods

The critical velocity is when the velocity on the outer edge of the floc particle is equal to the floc settling velocity. Any velocity exceeding the critical velocity is when floc roll up begins.

In order to experimentally determine the critical velocity at which floc roll up begins, flow rates through the tube settler were increased incrementally utilizing a ramp state function in process control software.

By incrementally increasing the flow rate through the tube settler, we can compare the effluent turbidity performance over time. A critical velocity could be identified based upon effluent performance and compared to our theoretical model.

Using the same experimental apparatus as was used in Summer 2009 and Spring 2009, and the ramp state process controller function, we hope to understand if our theoretical model of floc roll up behavior describes system behavior. Ultimately, we hope to minimize the floc roll up in the plate settlers and further reduce the effluent turbidity. Also, we want to potentially understand how to create flocs that will experience less roll-up and have better performance.

Results and Discussion

By running the ramp state function on different tube settler diameters, we hope to further develop the relationship between plate settler size and floc roll up.

Experiment 1: Ramp State with 9.5 mm Plate Settler Tube Diameter

This experiment started with a flow rate of 6 mL/min and over the course of 24 hours, gradually increased to a flow rate of 50 mL/min. This flow rate range corresponds to a capture velocity range of approximately 0.127 mm/s to 1.053 mm/s.

t

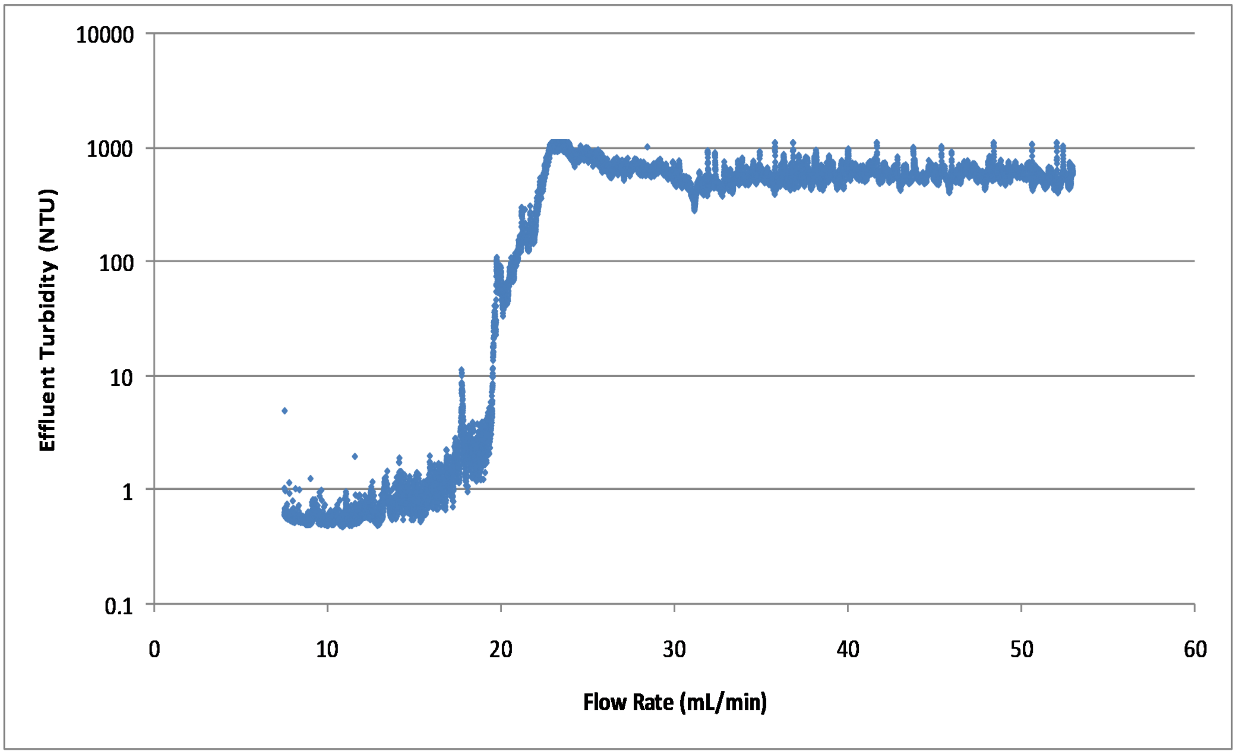


Figure 1: Effluent Turbidity vs. Flow Rate

Experiment 1 Conclusions

The very clear spike in effluent turbidity observed at a flow rate of approximately 18 mL/min represents the point at which the floc particles began to roll up the tube settler, which was confirmed visually in the experimental apparatus. The velocity represents the critical velocity. At a certain velocity, the turbidity stabilizes, and stops increasing. This is because, at a certain point, the number of flocs rolling up in the settler cannot increase anymore and thus the turbidity cannot increase anymore.

These experimental results can be compared with the expected results of our theoretical floc rollup calculations. Theoretical calculations for a 9.5 mm diameter plate settler tube predict that floc rollup should start to occur at a flow rate of 15.693 mL/min. Comparing this theoretical value with the observed floc rollup flow rate of approximately 18 mL/min above, we see that the experimental observations support the theoretical calculations quite well, within experimental error.

Experiment 2: Ramp State Function with 15.3mm Tube Settler Diameter

This experiment starts with a flow rate of 6 mL/min and gradually increases to a flow rate of 140 mL/min over the course of 24 hours. This flow rate range corresponds to a capture velocity range of approximately 0.127 mm/s to 2.963 mm/s.

t

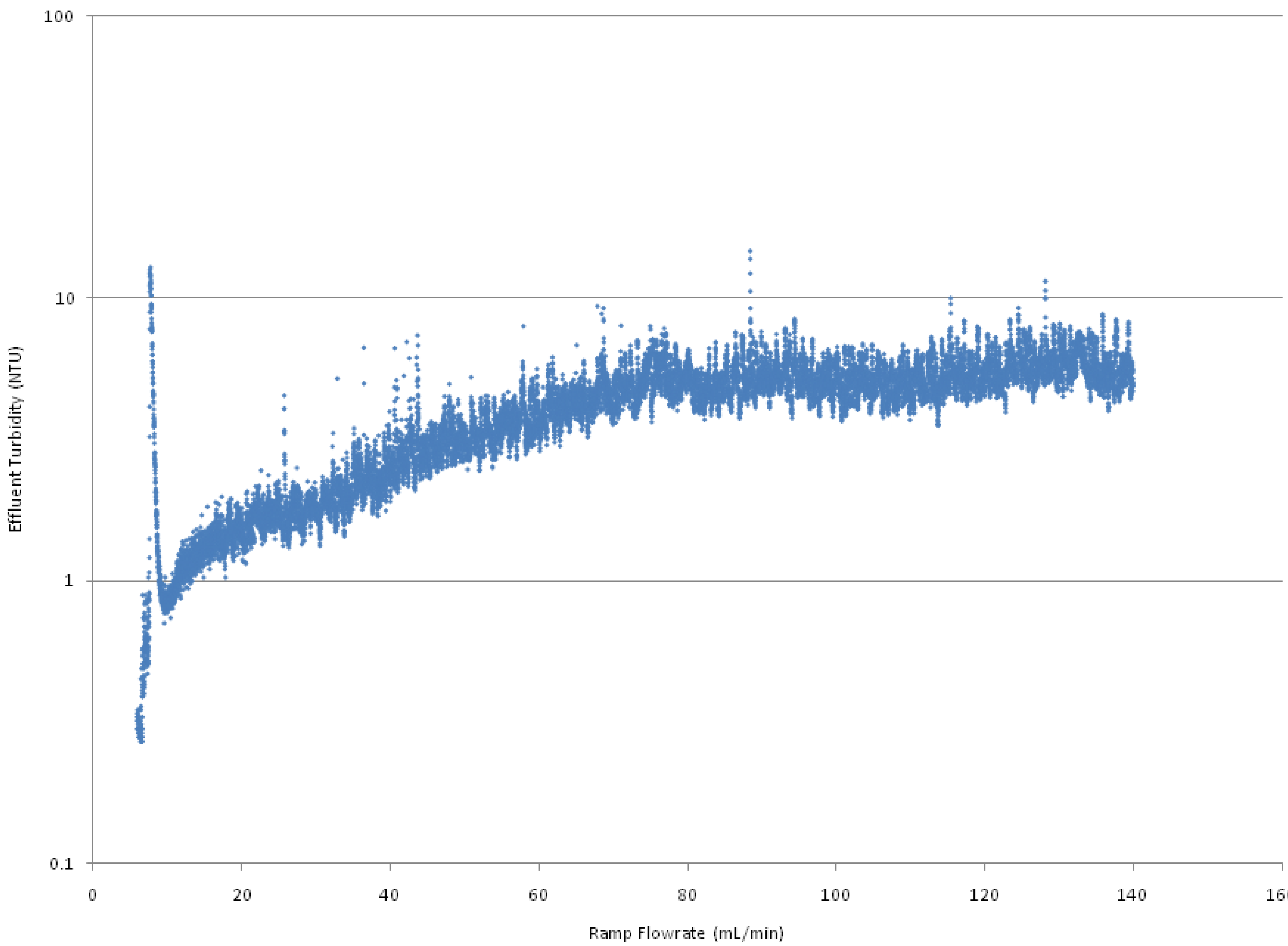


Figure 2: Effluent Turbidity vs. Flow Rate

Experiment 2 Conclusions

Unlike the results for the 9.5mm tube, there is no obvious sharp increase in effluent turbidity. Although the turbidity of the effluent water does increase as the flow rate is increased, this change in turbidity is minimal compared to the 9.5 mm tube. The effluent tubidity is slightly higher than our standard of 1 NTU, but this is not a significant enough difference to assume that floc rollup has occured. Furthermore, theoretical calculations for a 15.3 mm diameter plate settler tube predict that floc rollup should start to occur at a flow rate of 65.557 mL/min. Analyzing the results plotted in Figure 2 above with this in mind, we see no visual confirmation of this in the form of a sharp peak in turbidity in the data around the predicted flow rate. Therefore, we have concluded that there is no clear evidence that floc rollup has occured. Due to the fact that the predicted values from our theoretical model calculations matched the observed results for the 9.5 mm tube quite well, we propose running more experiments with the 15.3 mm tube to verify whether the above discrepancy was due to experimental error or a problem with the theoretical model in predicting floc rollup in larger diameter tubes.

Troubleshooting

No labels

1 Comment

Matthew William Hurst

With this page you should compare you theoretical calculations to the data you obtained. Does the data make sense or not?

t

PSS Troubleshooting

Created by Elizabeth Hope Tutunjian, last modified on Dec 09, 2009

Troubleshooting

Over the course of the semester, our team experienced many technical challenges that impaired our ramp state experimental results. We have outlined three major challenges and possible solutions below.

Initial Turbidity Peaks in Data

Problem

Analyzing the effluent turbidity vs. flow rate plots collected following ramp state experiments, a single sharp initial peak in effluent turbidity was observed for most trials regardless of the tube diameter used.

Proposed Solutions

Our team has proposed two reasons for this observed peak in turbidity. One possible reason is that the tube settlers in our apparatus do not begin "pulling up" water until the ramp state initiates. A second possible reason is that the floc blanket formation time set in the process controller method is not long enough to ensure that a thick enough floc blanket is formed before the ramp state initiates. Our team has proposed experimenting with increased floc blanket formation times, approximately 8 hours as opposed to the original 6 hours.

Influent Water and Clay Mixer

Problem

During the semester, our influent water-clay mixer malfunctioned and needed to be replaced. However, our team continued to proceed with experiments until a new mixer was ordered and received. Without the mixer, our system ran through our concentration clay stock solution at a much quicker rate in order to maintain an influent water-clay solution of 100 NTU without a mixer.

Proposed Solution

In the event that future teams experience a similar problem, we suggest assigning a team member to be responsible for monitoring the rate at which the system runs through the clay stock using process control software and/or adjusting the concentration of clay in the solution as necessary. Although the problem we experienced went away once we received a new mixer, assigning a team member to such a role will be helpful in the event that future teams decide to experiment with influent turbidities greater than 100 NTU.

Ramp State Time

Problem

In order to get a complete full run for an experiment, we decided to temporarily decrease the ramp time to two hours for our ramp state functions. This created a problem with the smaller diameter tubes because tubes with smaller diameters use lower flow rates in the ramp state function. Because these flow rates are so low, the residence time in both the tube settler and the turbidimeter becomes significant.

Proposed Solution

When designing future experiments in process controller, it is important to consider these residence times when determining the ramp time. In order to determine the ramp state time that should be used (it should be minimized to reduce potential error with the apparatus), a successful experiment needs to be completed. We are currently working to collect data for a successful

No labels

1 Comment

Matthew William Hurst

With all of these problems listed, I think it is very important that your team not only identify the problems but identify solutions on here and quantifiable ways that the problems you mentioned can be ameliorated in the future. I would also like some of your writing to be more specific in the problems you encountered so we can help you avoid them in the future.

When you say that clay concentration was not sufficient, what is a way you can quantify what is sufficient over your experimental run? We can calculate all of these values in process control software, but we first need to make a list of all of the parameters that could fail that we have control over so for example if we run an experiment with higher turbidity we know how concentrated the clay stock needs to be so that we don't run out.

Another general comment is that I noticed that the process controller file has gotten very messy. I would strongly urge that before we run experiments next semester that we edit the process control file so that it is more user friendly with these calculations as checks before we run the floc blanket apparatus.