# Flocculator and Sedimentation Optimization

January 11, 2012

**Abstract**

The addition of floc blankets and stacked rapid sand filters to the AguaClara suite of technologies provides an opportunity to redesign flocculation and sedimentation to be more cost effective.

| | |
|---|---|
| Students | 4 |
| Skills | CEE 4540, fluid mechanics, process controller, data analysis |

## 1 Introduction

The design of water treatment plants has not been optimized for reduction of water waste, minimization of chemical use, minimization of overall carbon and ecological footprint, or minimization of construction costs. The design algorithms that have been generated as part of the AguaClara Design Tool facilitate the analysis of construction costs for a given design. The more complex optimization involves changing key expert input parameters. The goal of research with the floc/floc blanket/plate settler apparatus is to test options for reducing the overall construction and operating costs of the AguaClara facilities. Reduction of construction costs will require a reduction in material usage and thus will likely correspond with a reduction in carbon and ecological footprint.

The addition of the SRSF to the treatment train now gives us a new target for settled water quality. The SRSF has a pC* of 1 (needs to be confirmed) and thus it can polish 3 NTU water to 0.3 NTU and meet the USEPA standard. Thus our goal is to design a cost effective flocculator/floc blanket/plate settler system that consistently produces water with less than 3 NTU. The size of the sedimentation tanks can be reduced if it is acceptable to use a higher upflow velocity through the floc blanket. Preliminary evidence from the ENGRI 1131 water treatment plant competition during the fall of 2011 suggests that it may be possible to significantly increase the upflow velocity from the current value of $1\ \frac{mm}{s}$. The flocculator could be made smaller if we could increase the number of collisions by increasing the floc volume fraction. The floc volume fraction could be increased by implementing a floc recycle from the floc blanket or the floc hopper back to the beginning of the flocculator. The required collision potential can also be decreased given that it isn't necessary to flocculate very low turbidity suspensions and that it isn't necessary to make such large flocs given that additional flocculation occurs in the floc blanket. It is very likely that the flocculator can be substantially reduced in size perhaps even by a factor of 10.

To test these ideas we need to build a new apparatus that incorporates all of these processes including tube settlers that return solids to the floc blanket.

## 2 Experimental Apparatus

A new apparatus will be required to test the optimal reactor parameters. The sedimentation tank can be a vertical 1" diameter transparent PVC pipe. The plate settler can be a 1" diameter tube settler made of transparent PVC pipe connected to the vertical PVC pipe with a $45^{\circ}$ elbow. The capture velocity for the tube settler can be easily changed by having multiple effluent ports along the top of the tube settler. Thus the effective length of the tube settler can be selected by choosing which port to activate. These ports can be activated by solenoid valves. Ideally the floc weir could be adjustable height. Perhaps a small diameter vertical tube for a floc hopper can be passed through the side wall of the compression fitting system that is used for the inlet to the sedimentation tank. The floc hopper will need a waste port as well as a recycle line that is pumped back to the beginning of the flocculator. The flocculator tube will have multiple inlet points and the inlet points will be selected by solenoid valves. Thus it will be possible to vary the collision potential of the flocculator by changing the length of the coiled flocculator tube that is in use.

## 2.1 Source water

The source water will be temperature controlled Cornell tap water amended with kaolin clay. The kaolin clay will be added from a concentrated stock suspension with a pinch valve. The raw water will be circulated through a turbidimeter by a small centrifugal pump to reduce our need for peristaltic pumps. The algorithm for controlling the raw water turbidity will need to be improved so that it maintains a low coefficient of variation. This requires a high flow rate through the turbidimeter so that it responds quickly to changes in turbidity. The on time for the pinch valve that delivers clay to the raw water tank should be proportional to the target turbidity so that the raw water turbidity can be changed easily without needing to change the stock concentration or the control parameters.

Table 1: Range of parameters to test

| Parameter | Symbol | Method | Parameter Range |
|---|---|---|---|
| Flocculator length | $L_{Floc}$ | 5 solenoid valves to select the inlet location | 1 m, 2 m, 5 m, 10 m, 20 m |
| Sed upflow velocity | $V_{SedUp}$ | vary the flow rate through the entire plant with maximum collision potential and capture velocities | $1\,\frac{mm}{s}$, $1.5\,\frac{mm}{s}$, $2\,\frac{mm}{s}$, $2.5\,\frac{mm}{s}$ |
| Capture velocity | $V_{SedC}$ | 5 solenoid valves to select the outlet location | $0.1\,\frac{mm}{s}$, $0.2\,\frac{mm}{s}$, $0.3\,\frac{mm}{s}$, $0.4\,\frac{mm}{s}$, $0.5\,\frac{mm}{s}$ |
| recycle flow rate ratio | $\Pi Q_{FlocRecycle}$ | variable speed peristaltic pump on recycle line | 0, 0.02, 0.05, 0.1, 0.2 |
| Raw water turbidity | | pinch valve based on measured turbidity | $3\,NTU$, $500\,NTU$ |

# 3 Optimization Strategy

Our goal is to reduce the cost of construction of the AguaClara facilities. We can do that by reducing the total residence time in the floc/sed system. Currently the residence time of the flocculator is approximately $1000\,s$ (17 min) and the residence time of the sedimentation tank is approximately $2000\,s$ (33 min). The two critical operating conditions are low and high turbidity events. The constraint is that the turbidity must be reduced by the floc-sed processes in order to be less than the maximum that can be treated by the filter. Given a target of 3 NTU at the filter influent the floc-sed process must be

Table 2: Proposed order of experiments

| $L_{Floc}$ | $V_{SedUp}$ | $V_{SedC}$ | $\Pi Q_{FlocRecycle}$ | Turbidity | Goal |
|---|---|---|---|---|---|
| 20 m | $2\,\frac{mm}{s}$ | $0.2\,\frac{mm}{s}$ | 0 | $3\,NTU$ | Maintain floc blanket (if not successful, then reduce $V_{SedUp}$to $1\,\frac{mm}{s}$) |
| 20 m | $2\,\frac{mm}{s}$ | $0.2\,\frac{mm}{s}$ | vary | vary | Determine preliminary optimal recycle ratio. Recycle from floc blanket at 50 cm above sed tank bottom |
| vary | $2\,\frac{mm}{s}$ | $0.2\,\frac{mm}{s}$ | optimal | vary | Determine minimum flocculation length necessary to maintain a floc blanket and meet effluent standards |
| min | vary | $0.2\,\frac{mm}{s}$ | optimal | vary | Determine optimal (or maximum) upflow velocity that meets effluent standards |
| min | max | vary | optimal | vary | Determine optimal (or maximum) capture velocity that meets effluent standards |

able to capture some solids when the raw water turbidity is $3\,NTU$. The maximum turbidity that the floc-sed processes need to treat is at least $500\,NTU$ (and perhaps $1000\,NTU$). For this optimization study the two turbidity extremes to evaluate will be $3\,NTU$ and $500\,NTU$. The process controller must be able to switch between $3\,NTU$ and $500\,NTU$ automatically.

Optimization of 4 parameters (see 1) where performance is strongly influenced by all parameters will require an intelligent iterative approach. The first question to address is whether floc recycle can reduce the required residence time for the flocculator.

The high floc blanket concentration and high flocculator concentration when flocs are recycled suggests that the solids residence time will be extremely high especially during low turbidity events. It could easily take a week or more to build a floc blanket at 3 NTU especially if the turbidity leaving the sedimentation tank is not significantly reduced. Thus for the following experiments it may be necessary to build the floc blanket first using a 500 NTU raw water and then see if it is possible to maintain the floc blanket during the 3 NTU events. It is possible that the floc blanket will reduce in height after the switch to 3 NTU due to a gradual increase in floc sedimentation velocity. A decrease in floc blanket height does not necessarily mean that the floc blanket is failing or unsustainable.

The coagulant dose should be set to provide reasonably good performance and then should be held constant (one value for 3 NTU and another value for 500 NTU) for the following experiments. The proposed order of experiments is given in 2.

After obtaining the preliminary values for all parameters identify new research questions and devise experiments to further refine the recommendations for design of AguaClara facilities. Explore the optimal coagulant dose with and without floc recycle to see if the coagulant dose can be reduced when flocs are recycled. Develop a strategy to determine cost tradeoffs between these parameters. Perhaps the ratio, $\frac{\Delta pC*}{\Delta \$}$, could be measured for each parameter to determine which parameter has the most influence on the cost.

# 4 Equation development (a subset)

## 4.1 Floc Recycle Design

The concentration of the solids in a floc blanket is approximately $4 \frac{g}{L}$ although this is a function of the upflow velocity. The relationship between the required collision potential figure 1 and the clay concentration in the flocculator suggests that the flocculator collision potential could be significantly reduced if the clay concentration could be increased. Given the floc blanket solids concentration and a target flocculator clay concentration the recycle ratio can be estimated.

$$C_{Recycle}Q_{Recycle} + C_{Raw}Q_{Plant} = C_{Flocculator}\left(Q_{Recycle} + Q_{Plant}\right) \tag{1}$$

Normalizing the flow rates by the plant flow rate we obtain

$$C_{Recycle}\Pi_{Q_{Recycle}} + C_{Raw} = C_{Flocculator}\left(\Pi_{Q_{Recycle}} + 1\right) \tag{2}$$

where the recycle ratio $\Pi_{Q_{Recycle}} = \frac{Q_{Recycle}}{Q_{Plant}}$. Solving for the recycle ratio we obtain

$$\Pi_{Q_{Recycle}} = \frac{C_{Flocculator} - C_{Raw}}{C_{Recycle} - C_{Flocculator}} \tag{3}$$

We know that 100 NTU suspensions are easy to flocculate and it would be reasonable to test 1000 NTU suspensions. The relationship between kaolin turbidity and concentration at turbidities greater than 15 NTU was reported in the Summer 2011 Turbidimeter report to be

$$1NTU = 0.525\frac{mg}{L} \tag{4}$$

It is possible that floc-floc abrasion at high floc volume fractions produces an excess of colloidal debris and a high settled water turbidity. Thus there may be an upper limit on the optimal flocculator solids concentration.

The flocculator concentration as a function of the recycle ratio is shown in 2.

A recycle ratio of between 0.02 and 0.2 is a reasonable range to test. The floc could be recycled from the floc hopper or directly from the floc blanket. Recycle from the floc blanket would decrease startup time because flocs could be recycled before the floc blanket reaches full height. Given that reducing startup time is a goal it is likely preferable to recycle flocs from the floc blanket. The recycle line should withdraw flocs from a height that represents the minimum depth of a stable floc blanket. If the recycle line take flocs from too low of an elevation it will delay the formation of the floc blanket because the concentration of flocs in the flocculator will need to increase before the floc blanket will be able to form.

Recycling from the floc hopper is also difficult because the floc hopper concentration will vary widely depending on how the floc hopper is operated. It might be possible to design the floc hopper with a recycle line connected at the very bottom of the floc hopper and a drain line connected at a slightly higher elevation. This configuration might provide a stable source of a higher concentration floc slurry.

## 4.2 Flocculator Design

The velocity gradient, G, for the tube flocculator should be in the range of 30 to 100/s. The equations presented below can be used to assess the actual velocity gradients and corresponding energy dissipation rate in the flocculator. It may be desirable to change the tubing diameter if the resulting energy dissipation rate is far from the AguaClara design guidelines.

$$\overline{G} = \frac{64Q}{3\pi D^3} = \frac{16\bar{V}}{3D} \tag{5}$$

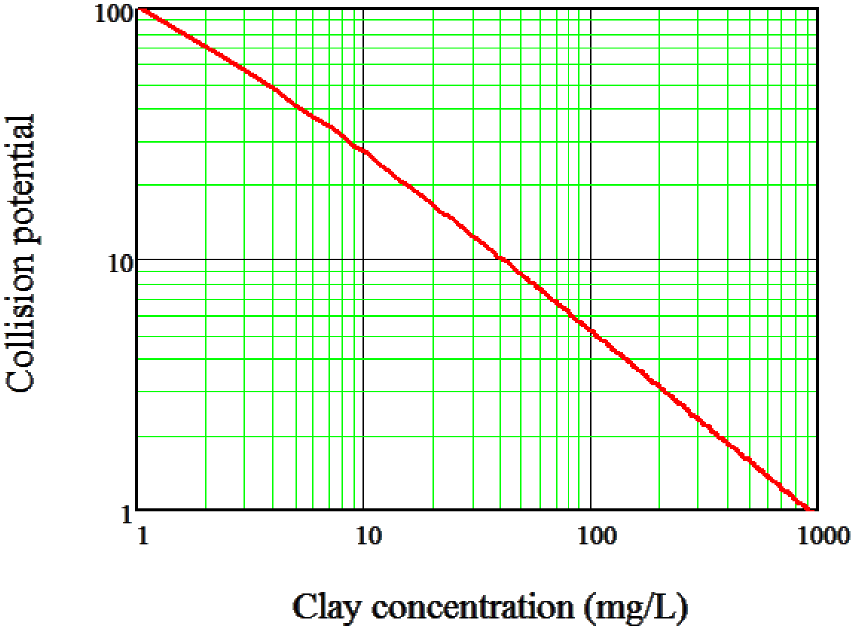

Figure 1: Required collision potential in $m^{\frac{2}{3}}$as a function of the clay concentration in the flocculator based on the fractal flocculation model.

The relationship between velocity gradient and energy dissipation rate for laminar flow is

$$\bar{\epsilon} = \bar{G}^2 \nu \tag{6}$$

Thus the average energy dissipation rate can be calculated from the velocity and diameter of the tube flocculator. Note that this approach neglects the additional energy dissipation caused by using coiled tubing.

$$\bar{\epsilon} = \left(\frac{16\bar{V}}{3D}\right)^2 \nu \tag{7}$$

The maximum velocity gradient occurs at the wall of the tube.

$$G_0 = 8\frac{\overline{V}}{D} \tag{8}$$

The corresponding maximum energy dissipation rate for a tube flocculator is thus

$$\varepsilon_{Max} = 64\left(\frac{\overline{V}}{D}\right)^2 \nu \tag{9}$$

The ratio of maximum to average energy dissipation rate for laminar flow is thus

$$\alpha_\epsilon = \frac{\varepsilon_{Max}}{\bar{\epsilon}} = \frac{9}{4} \tag{10}$$

The AguaClara designs currently use 10 $\frac{mW}{kg}$for the maximum energy dissipation rate. The corresponding $\overline{G}$ is

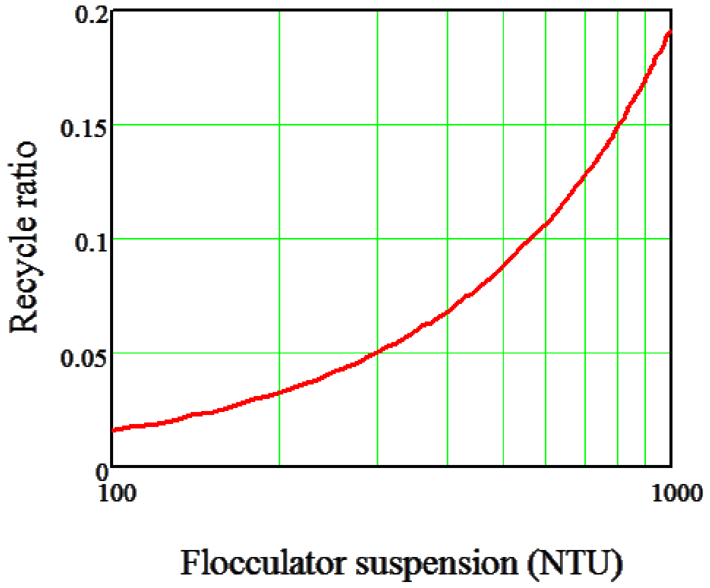

Figure 2: Recycle ratio required given low turbidity raw water (3 NTU) and a floc blanket concentration of 4 $\frac{g}{L}$.

$$\overline{G} = \frac{2}{3}\sqrt{\frac{10\,\frac{mW}{kg}}{1\,\frac{mm^2}{s}}} = 67\,{}^{1}\!/\!{}_{\mathrm{s}} \tag{11}$$

The required diameter of a laminar flow flocculator given a flow rate and a target maximum energy dissipation rate can be obtained by combining equation (9) with the continuity equation.

$$\varepsilon_{Max} = 64\left(\frac{4Q}{D^3\pi}\right)^2 \nu \tag{12}$$

$$D = \left(\frac{32Q}{\pi}\right)^{\frac{1}{3}}\left(\frac{\nu}{\varepsilon_{Max}}\right)^{\frac{1}{6}} \tag{13}$$

For a 2.5 cm diameter sedimentation tank with an up-flow velocity of 2 $\frac{mm}{s}$ the flocculator diameter should be 4.6 $mm$. A 0.25 $in$ inner diameter tube is reasonable.

The equations above do not account for the coiling of the flocculator tube. The Dean number, $\Pi_{De}$ is used to characterize coiled tubing.

$$\Pi_{De} = \frac{VD}{\nu}\left(\frac{D}{2D_{Coil}}\right)^{\frac{1}{2}} \tag{14}$$

Liu and Masliyah's model (1993) for Dean numbers less than 5000 gives the ratio of the friction factor of curved versus straight tubing.

$$f_{ratio} = \frac{1 + \left[0.0908 + 0.0233\left(\frac{D}{D_{Coil}}\right)^{\frac{1}{2}}\right]\Pi_{De}^{\frac{1}{2}} - 0.132\left(\frac{D}{D_{Coil}}\right)^{\frac{1}{2}} + 0.37\left(\frac{D}{D_{Coil}}\right) - 0.2}{1 + \frac{49}{\Pi_{De}}} \tag{15}$$

Head loss in the tubing is proportional to the friction factor, $f$, and the energy dissipation rate is proportional to the head loss. The energy dissipation rate for a coiled tube is equal to the energy dissipation rate for a straight tube scaled by the $f_{ratio}$.

The design of the jet of flocculated water entering the bottom of the sedimentation tank should be reevaluated based on our latest understanding of the role of the maximum energy dissipation rate. We are currently using a maximum energy dissipation rate, $\varepsilon_{Max}$, of 10 $\frac{mW}{kg}$ in the design of the flocculator and inlet to the sedimentation tank.

$$\varepsilon_{Max} = \frac{\left(\Pi_{Jet} V_{Jet}\right)^3}{D_{Jet}} \tag{16}$$

where $\Pi_{Jet}$ has a value of 0.4. Note that in the case of a tube discharging upward into the sedimentation tank that there is no vena contracta. The jet must be released at the bottom of a cone that collects all settled flocs and directs them toward the jet for resuspension. The flocculator tube should be able to simply discharge directly into the bottom of the sedimentation tank. Although a cone may be beneficial it isn't necessary based on results from the ENGRI 1131 competition.

The relationship between the jet energy dissipation rate and the diameter of the pipe that discharges the flocculator water into the sedimentation tank is highly dependent on the inlet geometry. For the case where the pipe discharges upward and there is no direction change (no vena contracta) as the fluid exits the pipe the equation is

$$D_{Pipe} = \left( \frac{Q_{Pipe}}{\epsilon_{Max}^{\frac{1}{3}}} \frac{4\Pi_{Jet}}{\pi} \right)^{\frac{3}{7}} \tag{17}$$

The maximum energy dissipation rate for the resulting jet is less than the energy dissipation rate in the pipe and thus it is likely that there is no additional constraint on the size of the jet exit. However, it is possible that a lower energy dissipation rate at the inlet to the floc blanket would help reduce floc breakup and reduce the residual turbidity.

## 5 Experiments

Scans over multiple parameters can be created by thinking of this as nested while loops where each the exit condition for each while loop sends the process controller to a unique exit state that serves as the increment state for the next higher level while loop. Creating the program for these scans will require careful thought and the program should be carefully constructed to be as simple and elegant as possible. The program can be tested by using artificially short times for the states to ensure that it cycles corrected through all of the states.

Each test would need to be run for at least two hydraulic residence times of the floc/sed system. After preliminary data analysis to confirm that the experimental results are valid, prepare to repeat the experiments using a second coagulant. Finally propose some experiments with variable doses of humic acid to assess the influence of natural organic matter on flocculation/floc blanket/tube settler performance.

Prepare a series of graphs illustrating the many relationships obtained in this large set of data. Ideally develop mechanically-based models describing the results. If that is not yet possible, develop empirical fits that will be useful for modeling the performance of an entire water treatment plant.

Each experimental run for a single set of conditions will produce one data point and a standard deviation that is the residual turbidity after passing through the tube settlers. The data analysis method will need to be simplified and streamlined to extract the correct data sequence from the data file and then calculate the average and standard deviation. The entire data record for an experiment should also be graphed and evaluated to ensure that the turbidity was stable and that trends are consistent with expectations during the transitions between experimental conditions.

# References

[1] Liu, S. and Masliyah, J.H. (1993). Axially Invariant Laminar Flow in Helical Pipes with a Finite Pitch. J. Fluid Mech. 251, 315-353.