Demo Plant Fall 2007 Report

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Abstract

The transparent demonstration plant is a good platform to perform flocculation experiments on, due to its manageable size and close approximation of an actual AguaClara water treatment plant. Experiments were done to investigate how more uniform shear in the flocculator - created by obstacles inserted in the vertical sections between bends - improves flocculation. Initial results showed that more uniform shear at the beginning of the flocculator caused effluent turbidity to decrease. Yet when the plant was modified to make it more robust and to make the results more repeatable, those initial results could not be replicated. Certain systematic errors in the initial experiments were eliminated and new errors were introduced. Subsequently, the plant was automated using ProCoDA Software to make it more time-efficient, and the desktop turbidity meter was replaced by an inline turbidity meter to eliminate unintended bias in readings. However, the results still showed that the performance of the flocculator did not improve by making shear more uniform. It is probable that the performance of the unmodified plant is already at the theoretical limit, and that improving flocculation at the beginning of the plant cannot decrease the turbidity of the effluent any further.

Keywords: demonstration plant, uniform shear, obstacles, improve flocculation

Introduction and Objectives

The demo plant was originally designed as an education and demonstration apparatus. This is the third version that has been build and is the most accurate representation of the actual plants located in Honduras. The previous demo plants were harder to follow and were less efficient.

The current demo plant is gravity-powered. The flow of fluids into the plant is regulated by constant head regulators. These constant head regulators are identical to the regulators used in Honduras. They regulate flow by keeping constant the difference in elevation between the top of the fluid in the regulator and the feed point. While the flow of fluids can be adjusted by changing the height of the feed points, the demo plant is designed to handle 100 mL/min of fluids.

The flocculator is open-top and is made of clear corrugated plastic. Each corrugation forms a channel that has a cross-section 10 mm long by 5 mm wide. Slits are cut in the corrugation to allow flow to weave through the device. The flocculator leads to the sedimentation tank made of the same corrugated plastic material. The corrugations here serve as the lamella. The flow through each lamella is kept uniform by a small orifice at the top of each channel. The orifice creates a significant amount of head loss and negates any difference in head loss between lamellas. The schematic of the demo plant is shown in Figure 1 below.

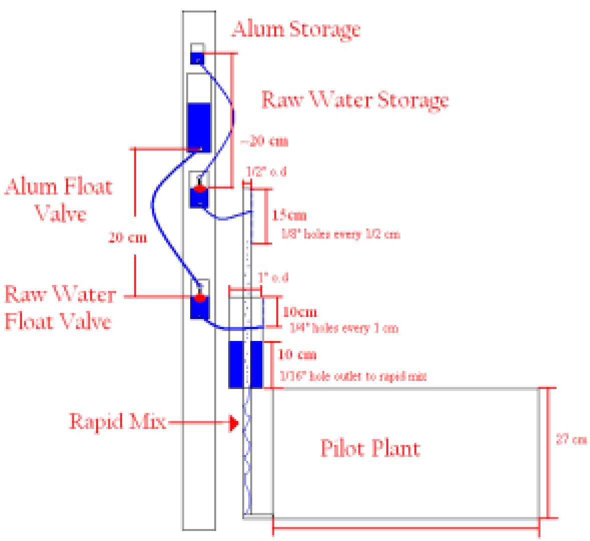

Figure 1: Dimensions and layout of the demo plant

The demo plant is of manageable size and is easy to operate. In addition, it is transparent and allows direct observation of the flocculation and sedimentation processes. These properties make the demo plant very suitable for flocculation experiments that must be carried out under controlled conditions, but in an apparatus that closely models the actual AguaClara water treatment plants.

Currently, most of the shear is provided by the 180° turns at the ends of the baffles. There is much less shear in the vertical sections between baffles. Thus, the difference between the maximum shear and the mean shear of the flocculator is significant. In addition, localized maximum shear at the 180° turns near the end of the flocculator is more than enough to break up flocs, although the mean shear is at a safe level. It is proposed that if the shear level across the vertical sections of the flocculator is more uniform, the flocculator will be more efficiently used and the size of the flocculator can be reduced. In addition, it will effectively reduce maximum shear near the end of the flocculator and reduce floc breakup.
In order to even the shear level, the flow path of water in the vertical section must be disrupted. One can introduce obstacles around which the water must flow. The initial approach was to experiment with disrupting flow at a small scale with the VFHF demonstration plant.

Procedures

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Clay Suspension Turbidity and Alum Dose

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For the Suspended Steel Nuts experiment, the concentration of clay in suspension and the alum dose were the same as those used during a public demonstration of the plant. The values were determined by Sara Schwetschenau et al to be optimal for public demonstrations, such that floc formation would be clearly visible.

For the subsequent experiments, the clay concentration was set to produce a suspension with constant known turbidity. The empirical correlation between clay concentration and suspension turbidity (Figure 2) was given by Ian Tse et al.

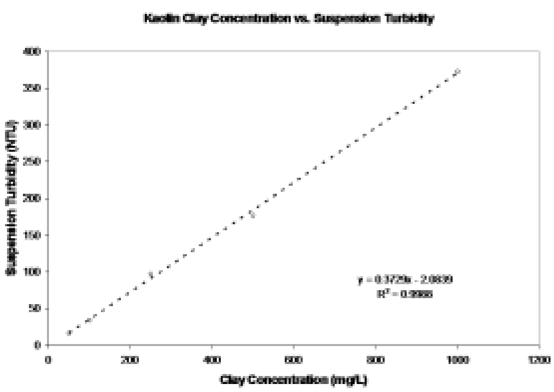

Figure 2: Correlation between clay concentration and turbidity

Suspension Turbidity $T = 0.3279 \times C_{clay} - 2.0839$

Values

- Suspension turbidity (T, NTU)
- Concentration of kaolin clay (C_{clay} , mg/L)

The alum dose was set according to the turbidity of the clay suspension (Equation 2). The volumetric flow of alum was then calculated using the dose, the concentration of the alum solution, and the flow of clay suspension into the plant (Equation 3).

Alum Dose $D = (1 + \log_{10} T) \times 15$

Values

- Alum dose (D, mg/ L)
- Suspension turbidity (T, NTU)

Alum Flowrate $$Q_{alum} = \frac{D \times Q_{clay}}{C_{alum}}$$

Values

- Alum dose (D, mg/ L)
- Flow rate of alum (Q_{alum} , mL/min)
- Flow rate of clay suspension (Q_{clay} , mL/min)
- Concentration of alum solution (C_{alum} , mg/L)

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Shear and Degree of Mixing

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Flocculation is facilitated by velocity gradients, or shear. Shear causes suspended particles to collide. Chemical coagulants, such as aluminum sulfate (alum) and poly-aluminum chloride (PAC), neutralize the negative surface charge of the particles and encourage them to adhere to one another after collisions. The two work in tandem to form flocs. Thus, higher shear causes more collisions and results in larger flocs. The number of collisions is also proportional to the amount of time that the suspended particles spend in the region of shear. Thus, longer time results in larger flocs.
It is necessary to have a quantity that measures the amount of shear that the suspended particles have been subjected to, since that determines the size of the flocs. This quantity is the product of shear (G, s^{-1}), and the amount of time spent in the region of shear (¿, s). The resulting dimensionless number (G¿) is a measure of mixing.

However, shear is also capable of breaking up flocs. Larger flocs, with greater cross-sectional areas, span larger velocity gradients and are subjected to higher forces. Thus, they are more susceptible to breakup than smaller flocs in the same shear. Therefore, the maximum shear that a floc can tolerate decreases with size. It is paramount to create high to promote flocculation without exceeding the limit that the flocs can tolerate.

The relationships between the relevant quantities for a vertical flow, baffled hydraulic flocculator are given below.

G average (per baffle)
$$\overline{G}_{baffle} = \sqrt{\frac{g \cdot h_l \cdot Q}{\nu \cdot h \cdot w \cdot b}}$$

Values

- Average shear ($\overline{G}$ baffle , s^-1^)
- Gravitational acceleration (g, 9.81 m/s^2)
- Head loss (h_l , m)
- Flow rate (Q, m^3/s)
- Kinematic viscosity of water (¿, 10^-6^ m^2/s)
- Height of flow channel (h, m)
- Width of flow channel (w, m)
- Baffle spacing (b, m)

$$G_{max} = \left(\frac{Q}{w \cdot b}\right)^{\frac{3}{2}} \sqrt{\frac{K}{2 \cdot \nu \cdot b}}$$

Values

- Maximum shear created (G_{max}, s^-1^)
- Minor loss coefficient (K)

Maximum shear allowed
$$G_{max,design} \approx \frac{1}{d_{floc}} \sqrt{\frac{8 \cdot \tau_{floc}}{C_D \cdot \rho_w}}$$

Values

- Maximum shear allowed (G_{max},design, s^-1^)
- Diameter of floc (d_{floc}, m)
- Shear strength of floc ($¿_{floc}$, 0.8 Pa)
- Coefficient of drag of floc (CD)
- Density of water ($¿_w$, 1000 kg/m^3)

$$\theta_{baffle} = \frac{w \cdot h \cdot b}{Q}$$

Values

- Residence time of baffle ($¿_{baffle}$, s)

Degree of Flocculator Mixing
$$G\theta = \sum_i \overline{G}_{baffle,i} \cdot \theta_{baffle,i}$$

Values

- Degree of mixing of flocculator (G¿)

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Suspended Steel Nuts (SSN)

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Hexagonal steel nuts, measuring 9 mm side-to-side and 3 mm thick, were tied into lines using dental floss. A wooden toothpick was tied to the end of each line to be used as the support to suspend the nuts in the flocculator. Each line had 13 nuts and 4 lines were made in total. The clay suspension was made by mixing 1000 mg/L of kaolin clay in tap water. The alum solution was made by dissolving 1000 mg/L of aluminum sulfate crystals in tap water.

The concentration of clay in suspension and the alum dose were the same as those used during public demonstrations of the plant. The clay concentration and alum dose were 1000 mg/L and 73 mg/L respectively. The flow of clay suspension was 100 mL/min as per plant design and the alum solution flow rate was 7.3 mL/min (Equation 3). The total plant flow was thus 107.3 mL/min.

The demonstration plant was set up with all valves closed. The 4 lines of nuts were inserted into the 5th to 8th channels of flocculator. The clay suspension and alum solution flow rates were set by inserting the feed tubes into the appropriate holes on the dosing apparatus. Next, the plant was filled with tap water and the weir at the outlet of the sedimentation tank was adjusted at the same time, such that the steady state level of water in channel 1 was near the top of the flocculator (Figure 3).

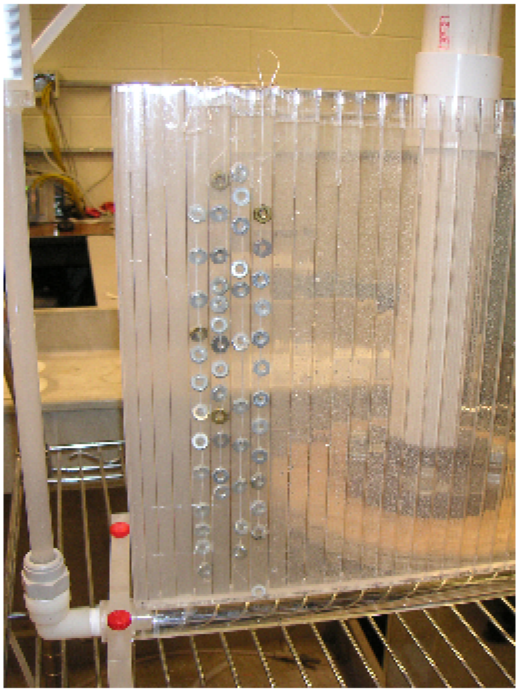

Figure 3: Plant setup of the Suspended Steel Nuts experiment.

To start the first experimental run, all the feed valves were opened simultaneously and the plant was undisturbed for 12 minutes to reach steady state. A sample of the effluent was then taken and its turbidity was measured using a Hach 2100N desktop turbidity meter. Two turbidity readings were taken consecutively, and the sample was agitated between readings. Immediately after taking the sample, the clay suspension tank was stirred to homogenize the suspension. Samples were taken at 2, 4, 6, and 8 minutes after the initial sampling. The clay suspension tank was stirred after taking each sample.

After taking 5 samples, the run was ended and the feed valves were closed. To prepare for the next run, the flocculator and sedimentation tank were emptied and rinsed with tap water. The clay suspension and alum solution tanks were topped up. The line of nuts furthest from the flocculator inlet was removed and the run was repeated. The experiment was performed with 4 to 0 line of nuts suspended in the flocculator.

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Suspended Tin Sinkers (STS)

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To replicate the results of the SSN experiments in a more rigorous manner, the experimental setup was extensively modified. Spherical Gremlin Green tin fishing sinkers were chosen to be used as obstacles. Nylon fishing line replaced dental floss since the former is stronger and more durable. The clay suspension and alum solution were fed to the plant using Cole-Parmer Masterflex® L/S peristaltic pumps (Figure 4) to ensure constant and more accurate flow rates. The clay suspension was also stirred throughout the experiment using a magnetic stirrer (Figure 5) to keep the turbidity consistent.

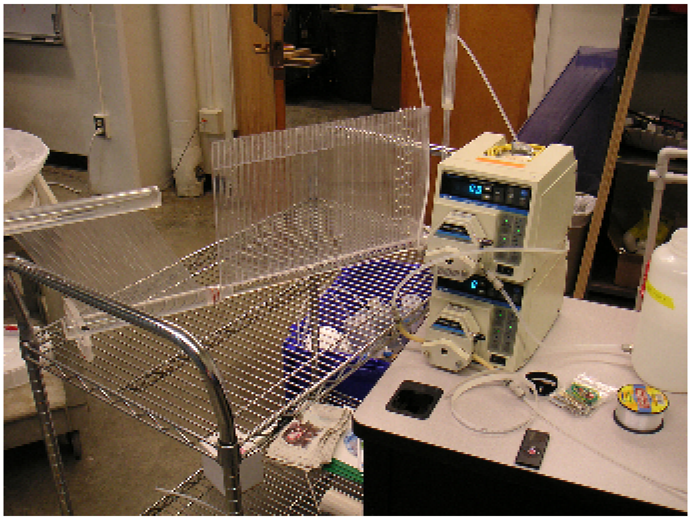

Figure 4: Modified experimental setup with peristaltic pumps.

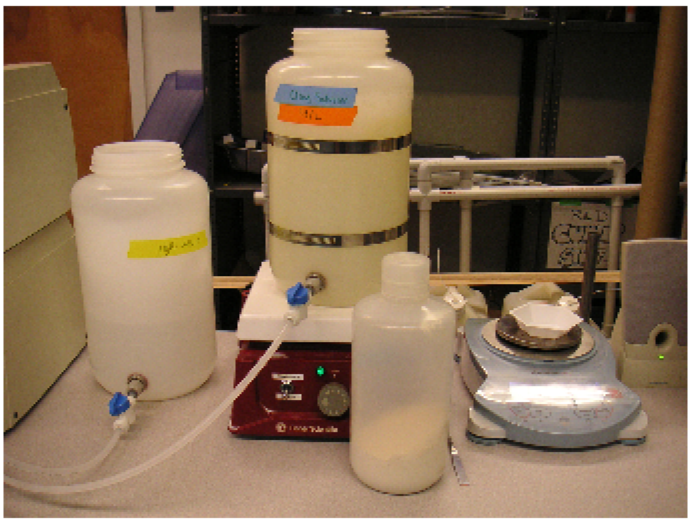

Figure 5: Constantly stirred clay suspension tank.

The fishing sinkers were tied onto nylon fishing lines. The protruding sharp ends of the sinkers were removed to make them more spherical. 4 lines were made with 11 submerged sinkers on each. An additional sinker was added to each line to be used as a clip to suspend the line from the top of the flocculator. The distances between consecutive sinkers on a line were very similar between lines Clay suspension was made by mixing 275 mg/L of kaolin clay in tap water to achieve a turbidity of 100 NTU (Equation 1). Alum solution was made by mixing 1000 mg/L of aluminum sulfate crystals in tap water.

The alum dose required to treat the 100 NTU suspension was calculated to be 45 mg/L (Equation 2). Therefore, the flow rate of alum was 4.5 mL/min (Equation 3). The clay suspension flow rate was 100 mL/min as per plant design, giving a total plant flow of 104.5 mL/min.

The alum solution was set atop a magnetic stirrer to dissolve any residual alum crystals prior to the start of each experimental run. The lines of sinkers were inserted into adjacent channels of flocculator, starting from the 3rd (Figure 4). The alum solution was then removed from atop the magnetic stirrer and the clay suspension was set atop the stirrer. The clay suspension would be constantly stirred throughout the run.

To start the run, the pumps were turned on simultaneously and the plant was undisturbed for 12 minutes to reach steady state. A sample of the effluent was then taken and its turbidity was measured using a Hach 2100N desktop turbidity meter. Two turbidity readings were taken consecutively, and the sample was agitated between readings. Samples were taken at 2 and 4 minutes after the initial sampling.
After taking 3 samples, the run was ended and the pumps were turned off. To prepare for the next run, the flocculator and sedimentation tank were emptied and rinsed with tap water. The clay suspension and alum solution tanks were topped up. The alum solution was set atop the magnetic stirrer in the meantime. The line of sinkers furthest from the flocculator inlet was removed and the run was repeated. The experiment was performed with 4 to 0 line of sinkers suspended in the flocculator.
An alternate experiment was also performed to reduce the contribution to flocculation by the baffles, in order to accentuate the contribution to flocculation by the obstacles. The experimental setup and procedures for the alternate experiment were identical to the original Suspended Tin Sinkers experiment, except that the clay suspension and the alum solution were fed to the 22nd channel of the flocculator (Figure 6). The lines of sinkers were suspended in alternate channels instead of adjacent channels, starting from the 23rd channel. The run time before the first sampling was reduced to 8 minutes.

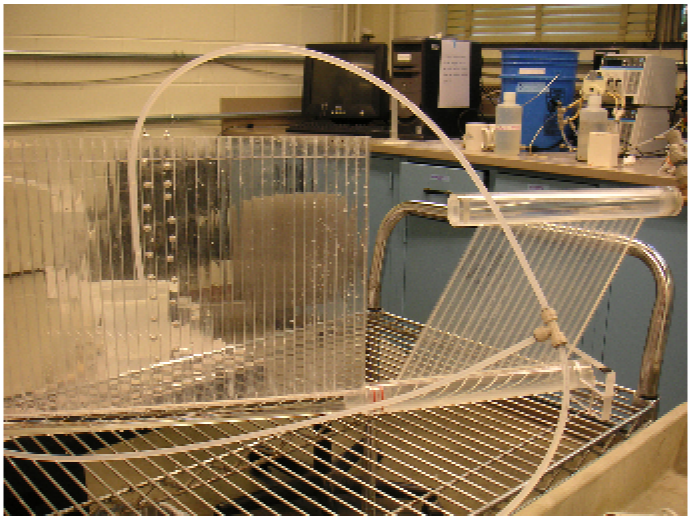

Figure 6: Alternate half flocculator setup.

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Suspended Tin Sinkers with Process Controller (STSPC)

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The STSPC experiment was performed to verify the results of the STS experiment. The obstacles, clay suspension and alum solution used were identical to those used in the original STS experiment. Process Controller was used to automate the experiment for better time-efficiency and precision. A MicroTOL inline turbidity meter replaced the Hach desktop turbidity meter in order to remove the unintended bias in manual turbidity readings (Figure 7).

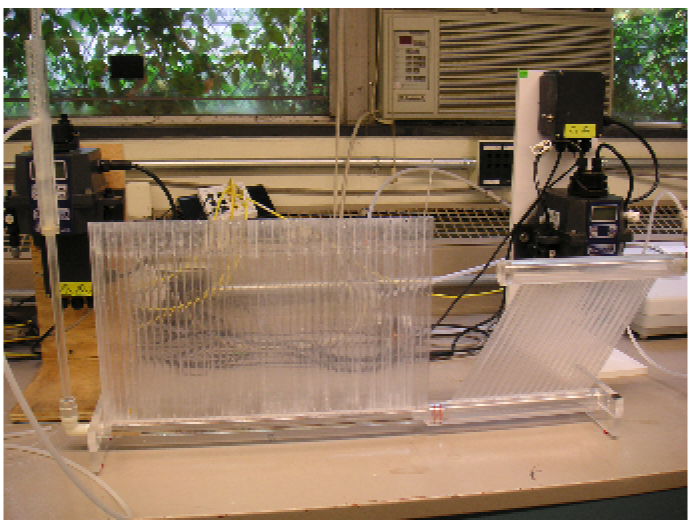

Figure 7: STSPC experimental setup.

The residence time of the setup was measured by pumping tap water into the empty plant at 100 mL/min and measuring the time elapsed before water starts flowing out of the outlet of the inline turbidity meter. The measured residence time was 900 seconds (15 minutes), which was longer than the 12 minutes estimate used in previous experiments.

The demonstration plant was set up and connected to the host computer. Within Process Controller, the total plant flow rate was set to 100 mL/min, comprising of 4.5 mL/min of alum solution and 95.5 mL/min of clay suspension. The resulting alum dose was 45 mg/L. The alum solution was set atop a magnetic stirrer to keep any precipitates in suspension throughout the experiment. The clay suspension was stirred constantly by a mechanical stirrer to keep its turbidity constant.

Process Controller was programmed to perform the experimental run in 3 sequential steps. Each step (state) had its own operating parameters (setpoints) and logic (rules). Effluent turbidity was measured by the inline turbidity meter and recorded onto a spreadsheet every 5 seconds. State 1 was programmed to fill up the plant with 100 mL/min of tap water for 900 seconds. The stirrers were turned on to ready the alum solution and clay suspension. The connecting tubes were manually purged of air and the level control device was manually adjusted such that the steady state level of water in channel 1 was near the top of the flocculator. After 900 seconds, Process Controller proceeded to State 2. It shut off the tap water pump and turned on the alum solution and clay suspension pumps for 1350 seconds. The stirrers continued to stir the alum solution and clay suspension. Finally, Stage 3 flushes the plant with 100 mL/min of tap water for 900 seconds, allowing for further experimental readings without introducing an excess of clay. This was done to ensure that the effluent turbidity readings were not affected by the accumulation of clay in the plant. The procedure was repeated 5 times for each number of lines of sinkers.

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Results and Discussion

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Suspended Steel Nuts (SSN)

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Visible improvement to flocculation was observed during the experiment. The steel nuts created turbulence and increased mixing. As a result, larger flocs formed earlier in the flocculator.

The effluent turbidities were plotted against time since initial sampling for different number of lines of nuts inserted into the flocculator (Figure 8). It was observed that for higher numbers of lines, the effluent turbidity was relative stable over time. For the lower numbers of lines, the effluent turbidity varied more. It is likely that the setups with fewer obstacles were more sensitive to sediment buildup within the flocculator and at the joint between the flocculator and the sedimentation tank (Figure 9). The sediment buildup changed the flow path and created new regions of high shear.

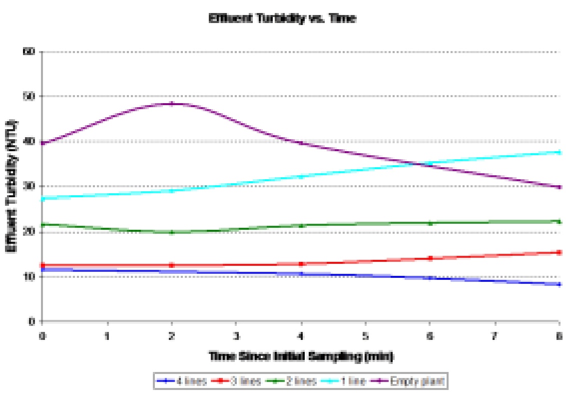

Figure 8: Effluent turbidities for different number of lines.

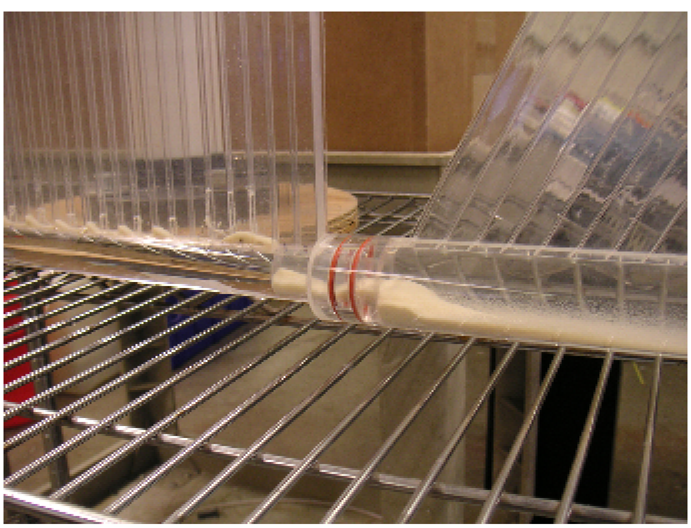

Figure 9: Sediment buildup.

The mean effluent turbidity decreased as the number of lines of nuts increased (Figure 10). This is consistent with the prediction that the more uniform shear level created by the nuts would increase flocculation, thus leading to effluent with lower turbidity. In addition, it was also observed that there were diminishing returns from inserting more obstacles. The effluent turbidity appeared to approach a limit, which was probably caused by big flocs breaking up into smaller ones in the last few channels of the flocculator (Figure 11). The limit could possibly be lowered by decreasing the shear at the end of the flocculator to reduce floc breakup.

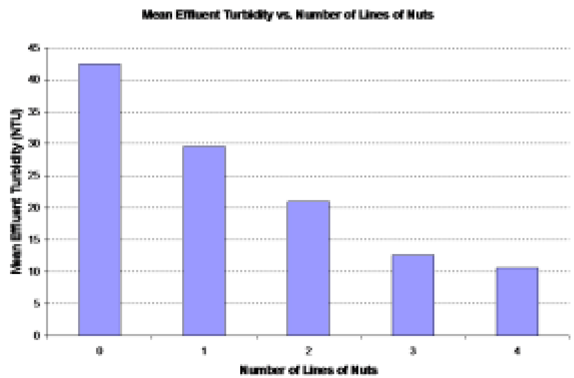

Figure 10: Diminishing returns from more obstacles.

Figure 11: Floc breakup due to excessive shear near the end of the flocculator.

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Suspended Tin Sinkers (STS)

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During the experiment, it was observed that when there were sinkers suspended in the flocculator, flocs formed earlier and the flocs were larger. There was also significant floc break-up in the last four channels right after the largest flocs were formed.

The mean effluent turbidities were plotted against the number of obstacles suspended in the flocculator (Figure 12). Results from the SSN experiment were included for comparison. The results of the STS experiment, including both full-flocculator and half-flocculator setups, did not show the same trend as the SSN experiment. The effluent turbidities did not show any correlation to the number of lines of obstacles in the flocculator.

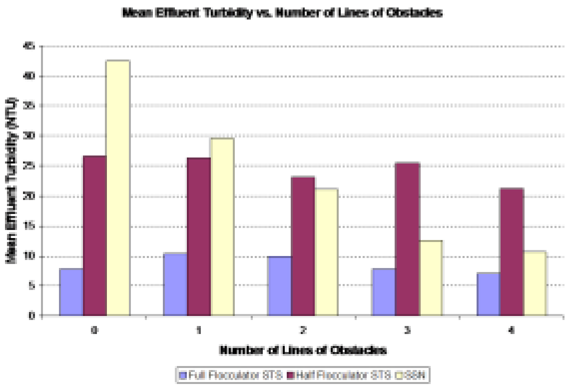

Figure 12: Comparison of STS and SSN results shows no similarity.

The use of pumps and the magnetic stirrer removed the systematic errors caused by the passive flow control modules used in the SSN setup. The flow control modules were not very accurate and the actual flow rates might not be the same as indicated on the column. In addition, the clay suspension and alum solution were not stirred consistently and had to flow through their respective constant head devices. As a result, they had significant time to settle. Thus, the amount of clay and alum entering the flocculator were likely to be less than expected. On the other hand, in the STS setup, peristaltic pumps ensured that the flow of alum solution and clay suspension into the demo plant were constant. The magnetic stirrer also ensured that the amount of clay entering the demo plant was constant. The alum solution was stirred vigorously between experimental runs and was thus kept at a more constant concentration.

However, unintended bias in the turbidity readings could not be eliminated since the Hach desktop turbidity meter continued to be used. The turbidity meter readings fluctuated constantly within a range of ±2 NTU, leaving it up to the observer to decide what turbidity to record. Finally, the system might not have reached steady state in 12 minutes. It is probable that the residence time is longer. Therefore, the data is showing the transient state.

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Suspended Tin Sinkers with Process Controller (STSPC)

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The observations during the experiments were very similar to those in the STS experiments. The sinkers caused larger flocs to form earlier, and the latter broke up in the last few channels of the flocculator.

The mean effluent turbidities are plotted against the number of lines of sinkers suspended in the flocculator. The results of the STS experiments are plotted alongside for comparison (Figure 13). The mean turbidities for the STSPC experiment were the averages of the steady-state turbidities of the experimental runs. The time-dependent turbidities for 2 lines of sinkers are plotted for reference (Figure 14). The results of the STSPC experiments did not show the same trend as the SSN experiment and are instead consistent with those of the STS experiments. In addition, the effluent turbidities did not show any correlation to the number of lines of obstacles in the flocculator.

Figure 13: Comparison of STS and STSPC results.

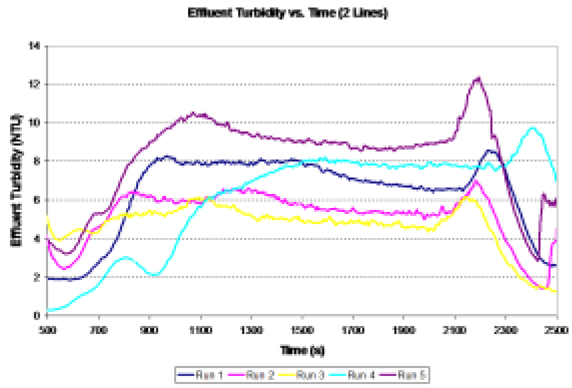

Figure 14: Time-dependent effluent turbidity for 2 lines of sinkers.

It is hypothesized that the performance of the flocculator is approaching the theoretical limit. The maximum size of flocs that leave the flocculator is determined by the maximum shear in the last few channels. In the STS and STSPC experiments, adding obstacles at the front of the flocculator created higher and more uniform shear in that section. As a result, larger flocs formed earlier. However, the maximum shear near the end of the flocculator remained unchanged. Therefore, they were too high for the larger flocs and caused them to break up. Consequently, the effect of adding obstacles at the beginning of the plant was negated. In addition, since fragments of broken flocs did not recombine as readily as fresh smaller flocs, it is even possible that the obstacles lowered the overall performance of the flocculator.

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Conclusions

The STS and STSPC experiments showed that the results of the SSN experiments were not reproducible. Although visually the obstacles seemed to improve flocculation especially earlier in the flocculator, the effluent turbidity did not decrease. It is probable that the unmodified plant is already operating near the theoretical limit. Thus, any improvement caused by the addition of obstacles is negated by excessive shear near the end of the flocculator. However, the reason for the trend in the SSN results remains unknown.

The effect of adding obstacles is therefore still not quantified. It is necessary to prevent the larger flocs from breaking up near the end of the flocculator to make the effect of adding obstacles apparent. This can be achieved by utilizing only part of the flocculator. In such a setup, the clay suspension and alum solution are fed into the flocculator at the halfway point of the flocculator. Without adding obstacles, the flocs formed will be significantly smaller than the largest possible floc that will not be broken up. Thus, any improvement caused by adding obstacles will cause an increase in the size of flocs leaving the flocculator. Consequently, the effluent turbidity will decrease.