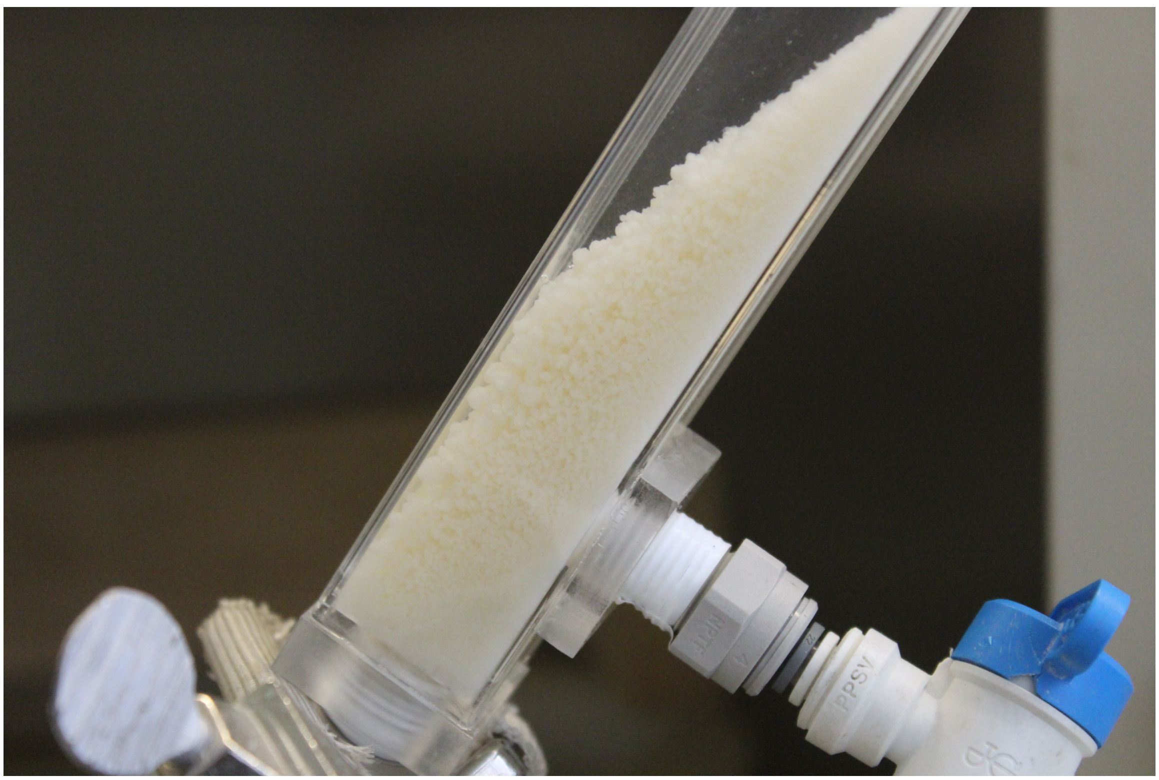
Final Project for CEE 4530

<u>The Effect of Raw Water Temperature Gradients on Flow Dynamics and Efficiency of Sedimentation in Tube Settlers</u>



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May 19th, 2014

1. BACKGROUND

AguaClara is an engineering program based at Cornell University that develops sustainable water treatment technology with current applications in developing countries. In Honduras, one of the countries with AguaClara technologies, the treatment plant at San Nicolas experiences raw water with a temperature gradient of around 1°C/hr during warming and cooling portions of a day. These gradients are primarily caused due to the approximately 15km of piping that brings raw water to the plant, much of which is exposed to the sun.

Agua Clara plants use sedimentation tanks with floc blankets and plate settlers. The temperature gradient during warming periods causes a circulation current to form in the vertical-flow sedimentation tank, due to the effect of continually warmer water displacing colder water. This current in the tank at San Nicolas causes flocs to aggregate on one side of the tank and rise up to the top with the hotter, less dense water; hence the effluent water leaving the tank is not sufficiently clean. Our experiment is motivated by this problem, with the goal of studying the problem's origins and providing initial research towards its solution.

2. OBJECTIVES

Our project aims to explore the effect of a temperature gradient in the influent water on tube settler flow dynamics and sedimentation efficiency, in order to evaluate difficulties Agua Clara is facing with sedimentation in San Nicolas. Our experiment serves two purposes: (1) To simulate the tank of plates settlers in an AguaClara Plant via a square (in cross-section) tube settler, and (2) collect (qualitative) flow dynamics information, and (quantitative) effluent turbidity data for different temperature gradients of raw water to tube settler.

3. EXPERIMENTAL PARAMETERS

6 temperature gradients were chosen, along with a control of no gradient. Gradients were chosen to mimic those found naturally, thus we chose a spectrum from 0.5°C/hr to 0.75°C/hr, in 0.25°C/hr increments. Thus, the gradients we experimented with were:

- 0˚C/hr (control)
- 0.5˚C/hr
- 0.75˚C/hr
- 1˚C/hr
- 1.25˚C/hr
- 1.5˚C/hr
- 1.75˚C/hr

We hypothesize that the settler will show decreasing performance with larger temperature gradients.

4. EXPERIMENTAL DESIGN AND METHODS

4.1. Overview of Apparatus

The system begins at the raw water tank. Water is pumped from the tank through an influent turbidimeter. After the turbidimeter, coagulant is mixed into the raw water line, using micro tubing for coagulant dosing, and the mixture is sent through a flocculator, followed by a section of the flocculator that is immersed in a water bath in order to heat the water to the desired temperature. This flocculated water is then sent through a tube settler, followed by an effluent turbidimeter. Figure 1a shows a schematic of the set-up, and Figure 1b shows a photograph of the actual set up from the laboratory.

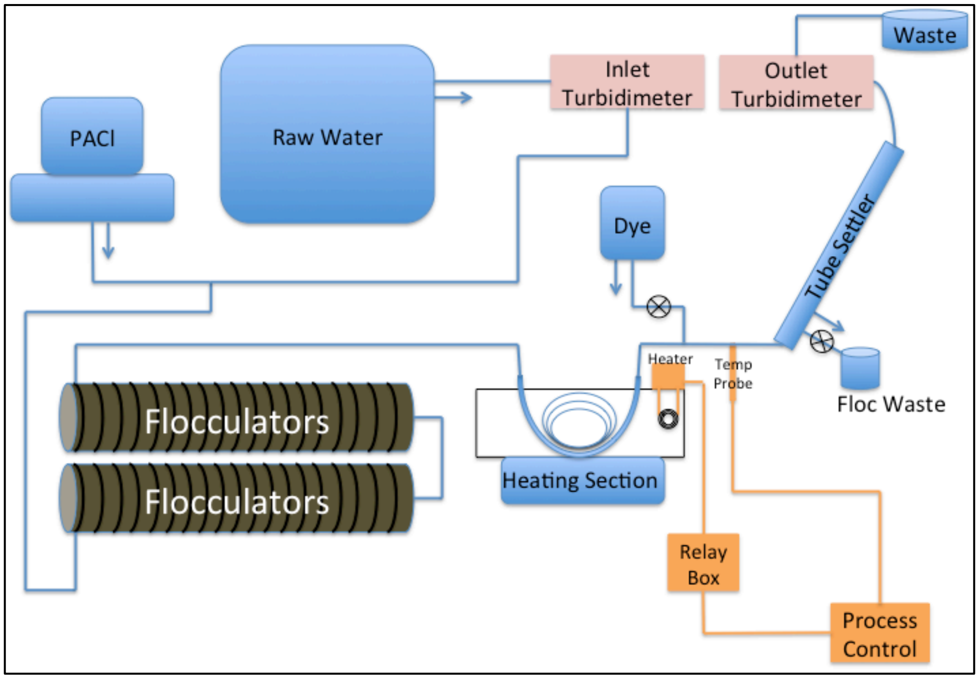

Figure 1a: Schematic of Laboratory Set-up

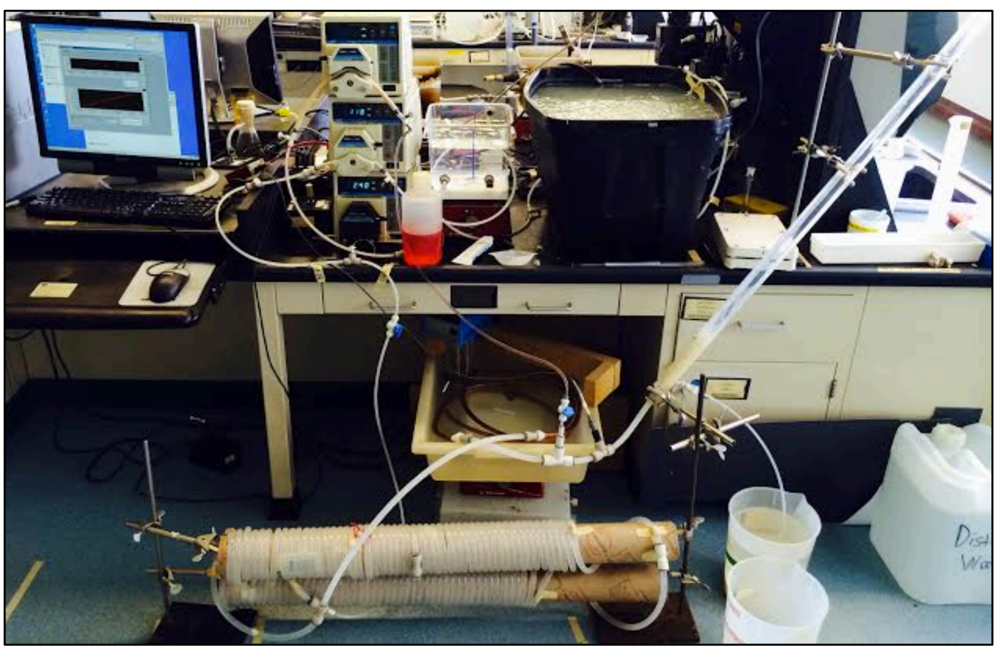

Figure 1b: Actual Experimental Set-up in Hollister Teaching Lab

4.2 Flow Rate, Coagulant Dose, and Influent Turbidity

For the flow rate through the apparatus, our constraint was the minimum flow rate required for the Turbidimeters. The Turbidimeters required a minimum flow rate of 100mL/min; we thus decided on a flow rate of 120mL/min. We next had to calculate the distribution of the flow rate between the raw water and coagulant dose. For the coagulant dose, we required a concentration of 10mg/L within the apparatus. With this concentration, we determined that a 500mg/L solution would fulfill the concentration requirement. Using conservation of mass, we calculated the flow rate needed of the coagulant solution:

$$Q_{alum2} := Q_{Plant} \cdot \frac{C_{Plant}}{C_{alum}} = 2.4 \cdot \frac{mL}{min} \qquad \text{(Eq. 1)}$$

We subtracted this from the total flow rate and rounded up, because with larger tubing size, the peristaltic pumps lose accuracy greater than three significant figures. Therefore, the raw water was pumped at 118mL/min.

Before running the different trials however, we tested the accuracy of the peristaltic pump. We realized that the pump pulled 117mL/min when it was set at 118mL/min. Therefore during the experimental runs we set the pump at 119mL/min to achieve 118mL/min for the raw water. The pumping for the coagulant dosing however, was accurate: when we set the pump at 2.4mL/min, it actually pumped 2.4mL/min.

The last aspect of the apparatus setup was the control of influent turbidity. We used the following formula to calculate the mass of clay to add to water for a certain turbidity:

$$C_{Clay} = 1.73\ \frac{mg}{L \cdot NTU} \cdot target\ NTU = 1.73 \cdot 100\ NTU = 1.73\ mg/L \qquad \text{(Eq. 2)}$$

This equation however, produced a turbidity of 150 to 200NTU, but this did not cause any problems. Despite using a very large tank filled for each trial that was mixed using a submerged pump recirculating water in the tank, we replaced the used water during the trials every 30 minutes to prevent air bubbles from entering the system.

4.3 Flocculator

We used a laminar coiled-tube flocculator, and needed to ensure that successful flocculation would occur as the water flowed through. We follow the methods used by Tse et al. through this portion of the set up. First, we calculated for the velocity gradient inside the flocculator (G_S) with the following equation:

$$G_s := \frac{8 \cdot Q_{Plant}}{3 \cdot \pi \cdot \left(\frac{ID_F}{2}\right)^3} = 15.716 \frac{1}{s} \qquad \text{(Eq. 3)}$$

The input values are: the flow rate through the apparatus (Q_{Plant}) and the inner diameter of the flocculator tubes (ID_F). Q_{Plant} and ID_F equaled 120mL/min and 3/8 in respectively. We corrected this velocity gradient to account for the circular coils of the flocculator, this velocity gradient is defined G_C. We used the following formula:

$$G_c := G_s \cdot \left(1 + 0.033 \cdot \log\left(De\left(Q_{Plant}, ID_F, \nu, R_c\right)^4\right)\right)^{0.5} = 17.436\frac{1}{s} \qquad \text{(Eq. 4)}$$

The input values are: the velocity gradient inside the flocculator (G_S), the Reynolds number (Re) [which for our set up was calculated to be 267 – thus ensuring laminar flow), and a dimensionless constant called the Dean's number (De). As calculated above, G_S equals 15.716s^{-1}. The Dean's number was calculated using the following formula:

$$De(Q, D, \nu, R) := \sqrt{\frac{D}{R}} \cdot Re(Q, D, \nu) \qquad \text{(Eq. 5)}$$

where D is the diameter of the flocculator tuding (also ID_F) and R is the diameter of the flocculator coils, 8.5 inches. We also calculated the residence time in the flocculator (θ) using the following formula:

$$\theta(Q, D, L) := \frac{A_F \cdot L}{Q} \qquad \text{(Eq. 6)}$$

where A_F (0.11in^2) is the cross sectional area of the tubing, L (110ft) the length, and Q (120mL/min) the flow rate. With G_C and θ, we calculated $G\theta$ as:

$$G\theta := G_c \cdot \theta\left(Q_{Plant}, ID_F, L_F\right) = 2.083 \times 10^4 \qquad \text{(Eq. 7)}$$

This value calculates for flocculation effectiveness. If $G\theta$ is greater than 20,000, then there will be successful flocculation in the designed flocculator. Also, to ensure that this design would be viable in the laboratory, we checked for the head loss and energy dissipation in the flocculator. These were calculated to be 4.4cm and 0.364mW/kg for respectively, ensuring that our pumps could handle the design easily, and flocs would not unnecessarily break-up in the flocculator either.

The setup of the flocculation required some troubleshooting with the methods of coiling and preventing pinches in the tubing. If the tubing was left pinched, then turbulence could occur in the coiling that could lead to floc breakup due to high energy dissipation rates. Also, after setting up the flocculator, we recognized air bubbles in the tubing. These air bubbles could also lead to turbulent flow and floc break-up, and were therefore removed.

4.4 Heating and Process Control

To provide the water with temperature gradients, we connected 10ft of coiled copper tubing to the effluent end of the flocculator, and placed it in a controlled temperature water bath. Also, because we wanted to represent a realistic situation, we heated the water bath with a continuous ramp function rather than a step function. We were able to achieve this by using Process Controller software.

Process Controller requires a source for data feedback and a set of set points and states. For feedback, as seen in Figure 1a, we placed a temperature probe between the copper tubing and the tube settler. This let Process Controller know whether the temperature of the water was too high or too low. We programmed a linear ramp function into the software, with initial temperature, final temperature and the duration of the interval as set points, thus achieving the required gradients. The heater was connected to process control via a Relay Box, which gave Process Controller an on-off control over the heater.

The command sent by Process Controller to the relay box was based on the feedback data from the temperature probe and the ramp function it was following. If at a specific time, the temperature on the ramp function were higher than the feedback from the temperature probe (i.e., the temperature of the water should be higher than what it actually was), process control would send a command for the water heater to turn on. A command would be sent to turn off the water heater, if the temperature probe readings were too high (i.e., the water was hotter at that specific time than the set gradient required it to be).

Initially when we performed trials with the water bath, the heating of the water within the copper tubing was erratic. This was due to the fact that the water bath was only mixed when the water heater turned on. When the water heater was off, the water bath remained static, and heat transfer efficiency was poor due to poor mixing. Adding a stir plate and stir bar to the apparatus, fixed this problem, and we were able to achieve heating that followed the expected ramp more closely.

4.5 Tube Settler

For the tube settler, we needed to calculate for the length. We used the following equation, derived from AguaClara specifications for plate settlers, to calculate a length of 4.4 ft:

$$l_{TubeSettler} := \frac{b \cdot \left(\frac{v_{Up}}{v_{Cap}} - 1 \right)}{\sin(\alpha)\cos(\alpha)} = 4.412\,\mathrm{ft} \qquad \text{(Eq. 8)}$$

The input values are: the inner cross width of the square pipe (b), the vertical component of the velocity in the tube settler (V_{Up}), the slowest settling particle that the tube settler can reliably capture (V_{Cap}), and the angle of the tube settler (α). The inner width of the tube settler was 2.831cm, a property from the manufacturer, and chosen to resemble the spacing between AguaClara plate settlers (2.5 cm). V_{up} equals 0.3055cm/s and was calculated based on the velocity of the water in the tube settler and the angle of the tube settler. V_{cap} equals 0.12mm/s and is based on the value that AguaClara uses in their plants.

The setting up of the tube settler required machining and some troubleshooting. The tube required capping at both ends, and tapping at both ends and side. Our influent water came from the bottom through a tap for a ½ in diameter pipe, and exited from the top through a tap for a 3/8 in diameter pipe. The third tap, for a 1/8 in diameter pipe, was located on the end nearest to the influent and on the side facing the floor. This tap was used as the floc drain, to remove the constant buildup of flocs from settling. Due to the fragile nature of the acrylic tube, machining was difficult: Our first practice attempt cracked the pipe slightly, and so we decided to first machine the tube settler to 4.5 ft in case the tube would crack in the band saw. The tube held up, and we decided to use this length of settler for the experiment instead of risking further cracking by narrowing the margin. Another aspect was setting the tube settler at a 60° angle. With two stands, multiple clamps, and a protractor, we eventually achieved the desired angle.

4.6 Summary of Design Parameters

Table 1 summarizes the experimental design parameters derived in the discussion above.

Table 1: Summary of Design Parameters

Raw water	**Concentration**	100 NTU
	Flow rate	118 mL/min
Coagulant	**Concentration**	500 mg/L
	Flow rate	2.4 mL/min
Flocculator	**Inner diameter**	3/8''
	Length	100 ft
	G θ	20,830
Coiled copper tubing	**Inner diameter**	3/8''
	Length	10 ft
Tube settler (square cross section)	**Width**	0.94''
	Length	4.5 ft
	Angle of inclination	60°

4.7 Data Analysis

Once all dat was collected, we had to carry out extensive data analysis, where the final goal was to calculate pC* for each experimental run, defined in Equation 9**:**

$$pC^* = -\log\left({}^{\text{Turbidity}_{effluent,t+\theta}}\!\big/_{\text{Turbidity}_{influent,t}}\right) \qquad \text{(Eq. 9)}$$

where θ is the residence time of the plant.

A pC* of 1 corresponds to 90% treatment efficiency, pC* of 2 to 99%, and 3 to 99.9%, and so on. We arrived at a pC* value for each run using the techniques outlined below.

All data processing was carried out in Matlab (Appendix 1). Raw data for influent and effluent turbidity included large spikes. These were from when the Turbidimeters recorded a turbidity of -999 NTU due to air pockets or other electronic problems, and other large spikes in the *effluent* data were noted when air bubbles were pulled into the turbidimeter due to floc valve opening, dye was input into the tube settler, or agitation occurred in the turbidimeter vial. The turbidity values recorded during these times are clear outliers to the 5-hour trend, and were removed from the dataset so that calculated trends were not unduly affected.

Values recorded as -999 NTU were replaced with NaN (not-a-number) values in Matlab. To remove the other outliers due to air and dye interference, data was sorted by ascending order of effluent turbidity, and the last 1% of the dataset was replaced with NaNs. This corresponds to only removing values that are clearly larger than the normal trend of values, including the normal fluctuation seen in the raw data (Further discussion is found in the Results and Discussions section). The data was then re-sorted back in terms of run-time.

The raw data also includes many fine scale fluctuations in turbidity, as is common in time-series datasets. A moving average was thus calculated to remove these fluctuations in the data, thereby capturing the general trends in the data. For the averaging-window, we used a time-interval equal to the residence time in the tube settler, 7 minutes. We chose this time because it corresponded to an interval where a particle entering the turbidimeter at a specific instance would capture, via the averaging, the dynamics of all particles that would have been in the tube settler in that same period. Note that the moving average was calculated for every point in the turbidity data set – thus effectively smoothing the data. The algorithm used to compute the moving average also interpolated for, and replaced values that were NaNs. (Appendix 1)

Once the data was smoothed, pC* was calculated as in Equation 9, with an adjustment for the residence time of the plant, 25 minutes. Finally, averaging over the entire data for pC* for an experimental run gave an averge pC* value for that temperature gradient.

5. RESULTS AND DISCUSSION

5.1 Raw Data:

Raw effluent data from all experimental runs is shown in Figure 2, with faulty -999 values from the turbidimeter removed. Notice from the figure that there are large spikes in effluent NTU that are clearly over the general trend between 0-10 NTU. These spikes are mostly caused by air bubbles getting sucked into the turbidimeter due to a siphon being set up when the floc valve on the tube settler was opened to clear the tube of flocs. These spikes were removed using the methods described in the data processing section, but only after correcting for other deficiencies in data discussed below.

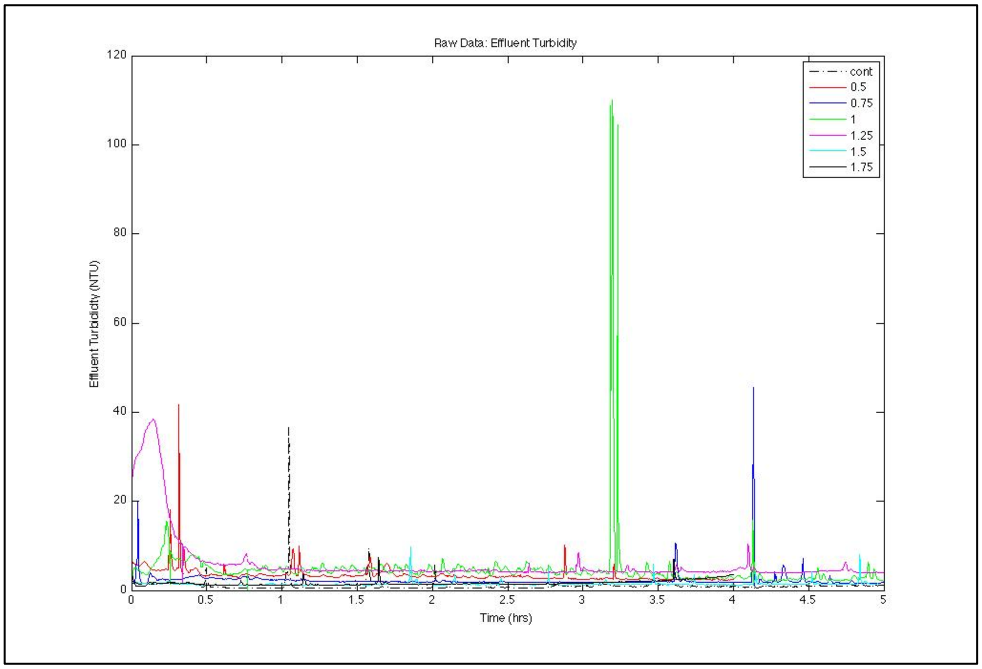

Figure 2: Raw Effluent Data

Figure 3 shows the same raw effluent data from Figure 2, but plots it to an axis limit of 15 NTU for better visualization. The broad spike in the 0.5 °C/hr run between 4 and 5 hours was caused by red dye, which was introduced into the set up for videography purposes. Realizing this negative effect on the turbidimeter, red dye was introduced into later runs only after the five hour mark, and the gradient was continued for another half an hour for videography purposes. During the 1.75°C/hr gradient, we noticed that the coagulant feed became clogged after around 4 hours, and made temporary changes to the feed line. The spike seen after 4 hours in the 1.75°C/hr data is due to this new set up, which performed worse, giving poorer flocculation (there were no big flocs formed) and thus poorer settling. A similar coagulant-feed issue occurred in the beginning of the 0.75°C/hr run, but this issue was solved to produce normal flocculation. Thus, in processing the data, we only used data from 0 to 4 hours for 1.75°C/hr and 0.5°C/hr, and 1-5 hours for the 0.75°C/hr run. Also, note from the figure that the data for run 1 shows larger fluctuations. This is because it was the first run we carried out, and we were making improvements to the system (such as introducing a stir bar in the heating tank and adjusting the curves of connecting piping to reduce minor losses and prevent floc break-up) while the experiment was running. While not an optimal solution, we had to do so because of the time constraints we had to carry out the entire experiment.

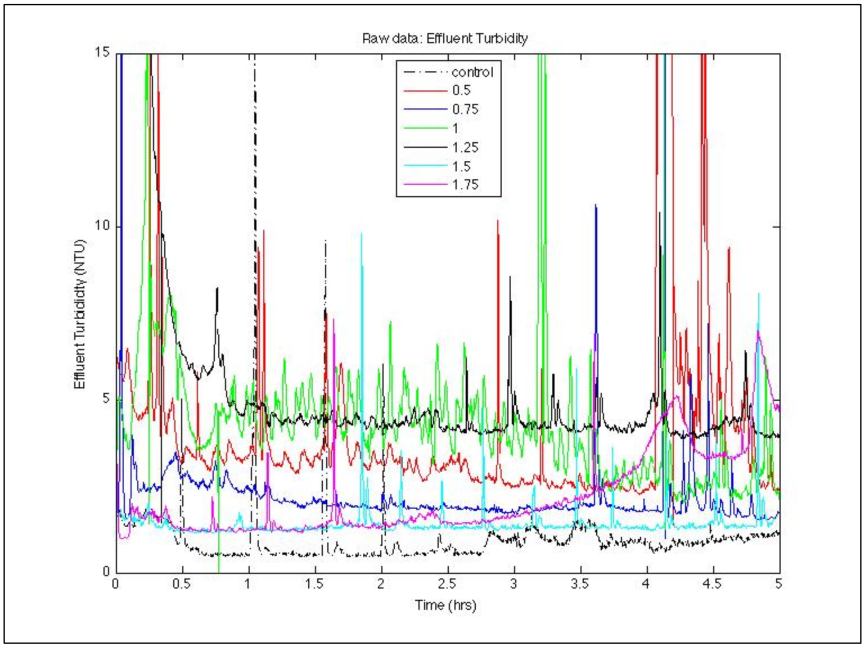

Figure 3: Raw Effluent Data, y-axis limited to 15 NTU

5.2 Degree of Temperature Control:

The set up involving the water heater, mixed water bath, and process control achieved good temperature control for the purposes of this experiment. Sample temperature plots are shown in Figure 4. Actual temperature input in the tube settler generally follows the required gradient, with fluctuations of about 0.2°C over about 6 minute intervals (clearly seen in Figure 5). The quick increase in the first five minutes is due to the water heating up from ambient room temperature.

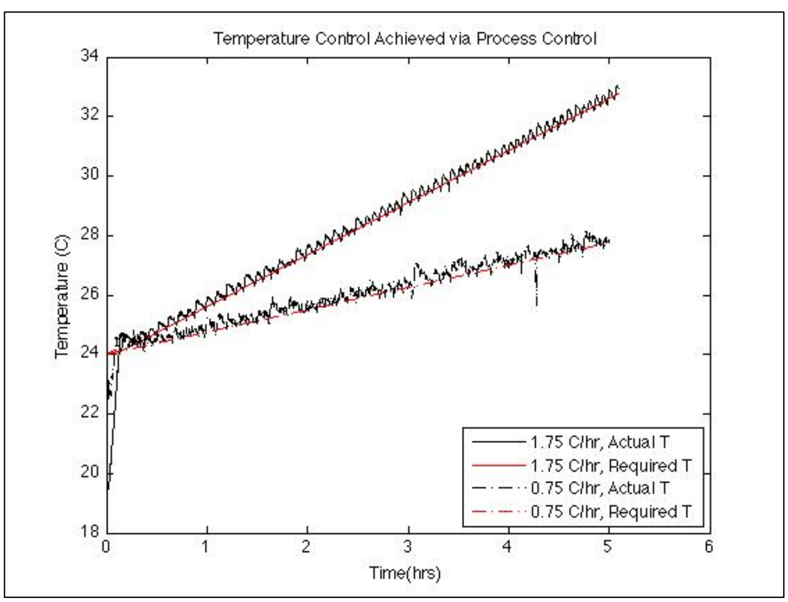

Figure 4: Temperature Gradient Achieved via Process Control

The small fluctuations over the general trend did not seem to effect effluent turbidity to a great degree. As seen in figure 5, effluent turbidity does not follow the same period or trend of fluctuations (even after adjusting for residence time in the tube settler): while the temperature control could be processed to an increasing, sinusoidal function, if need be, the fluctuations in turbidity are random. Thus, the smaller fluctuations in temperature have been mostly ignored in our data analyses.

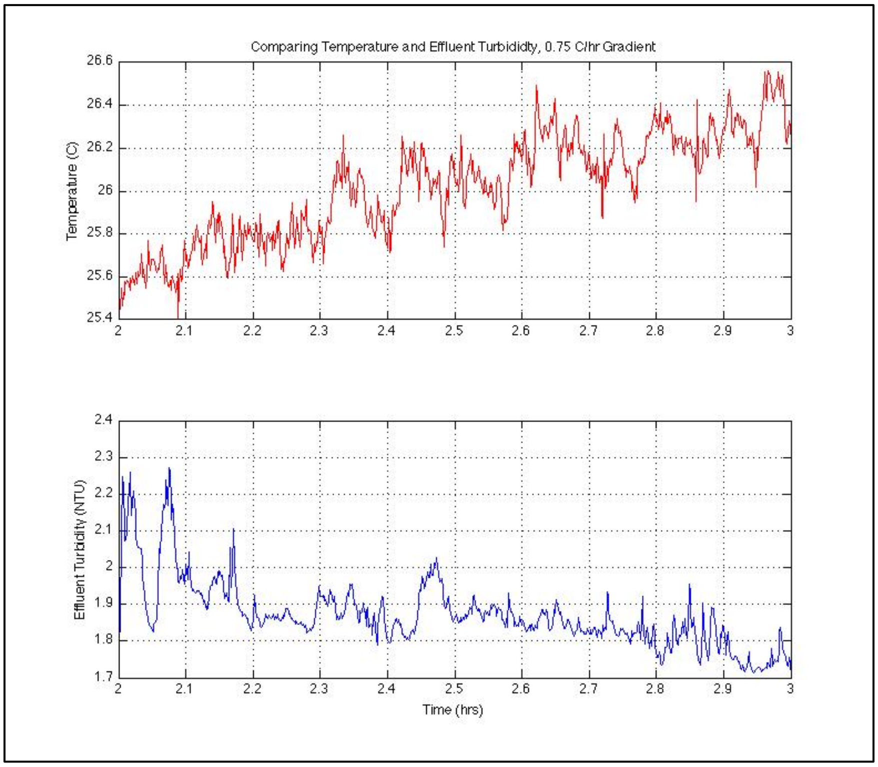

Figure 5: Comparing Temperature and Effluent Turbidity over small time steps, 0.75°C/hr gradient run

5.3 Treatment Efficiency:

The 'good' effluent data was then smoothed using the methods described earlier; Figure 6 plots this data. Once the large spikes have been removed, the smoothed data shows clear (mostly flat) trends and averages in effluent NTU. As noted before, the 1°C/hr run shows improving effluent NTU because it was the first run carried out, where the set-up was still being adjusted for leaks, timing of floc valve, heating efficiency, etc., and the 0.5°C NTU developed clogs through the run. It is notable that the control run shows consistent performance to below 1 NTU, the EPA standard for drinking water, while the rest of the runs are generally within 6 NTU.

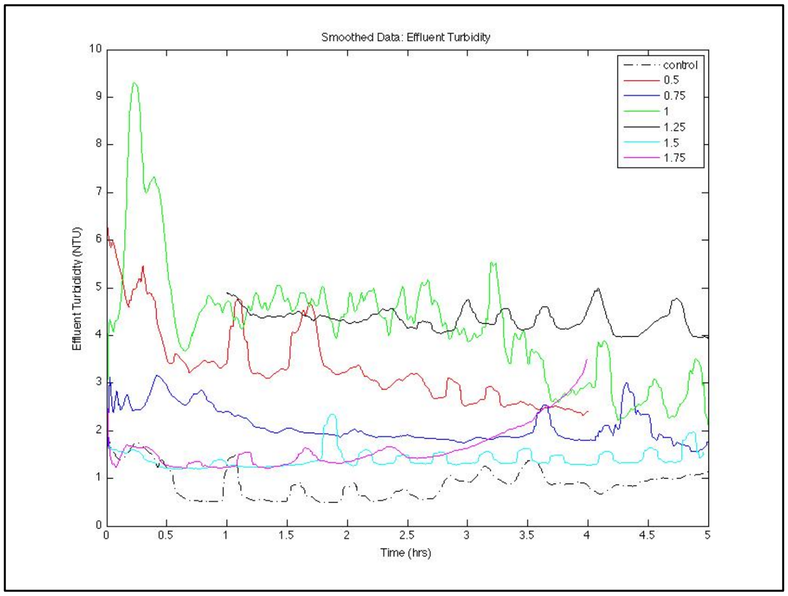

Figure 6: Smoothed Effluent Turbidity Data

The pC* (adjusted for residence time) for the duration of each experiment is shown in Figure 7; note that it begins at the residence time of the plant (25 minutes). The control, as expected, performs the best, with pC* hovering around 2.3 (corresponding to ~ 99.5% removal). The worst performing run had a pC* of around 1.6 (corresponding to a 97% removal). These trends are seen more clearly in Figure 8, which shows an average pC* for each run. This average has been calculated using pC* data from the 1.5 hour mark to the 4 hour mark, to maintain consistency between all runs, which have data beginning and ending at different times. Using data in this period also gives the set-up enough time to equilibrate, as apparent from Figure 7, with an initial lag seen in the pC* trend.

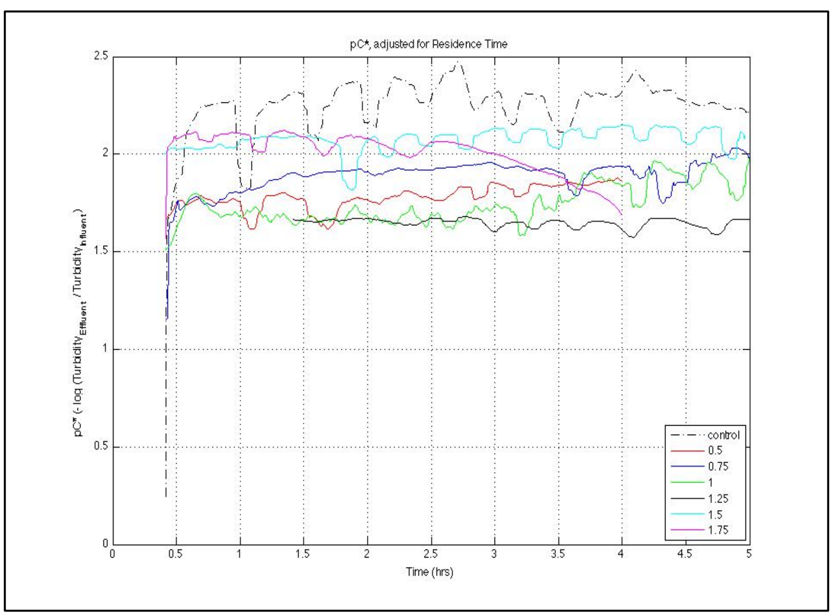

Figure 7: pc* for each temperature gradient, adjusted for residence

5.4 Trends in Data:

Figure 8 shows the final, major result from this experiment. There is a clear divide between the performances of the no-gradient (control) and the with-gradient runs; the control performs best with a pC* of 2.3. The data also shows a slight decreasing linear trend with increasing gradient.

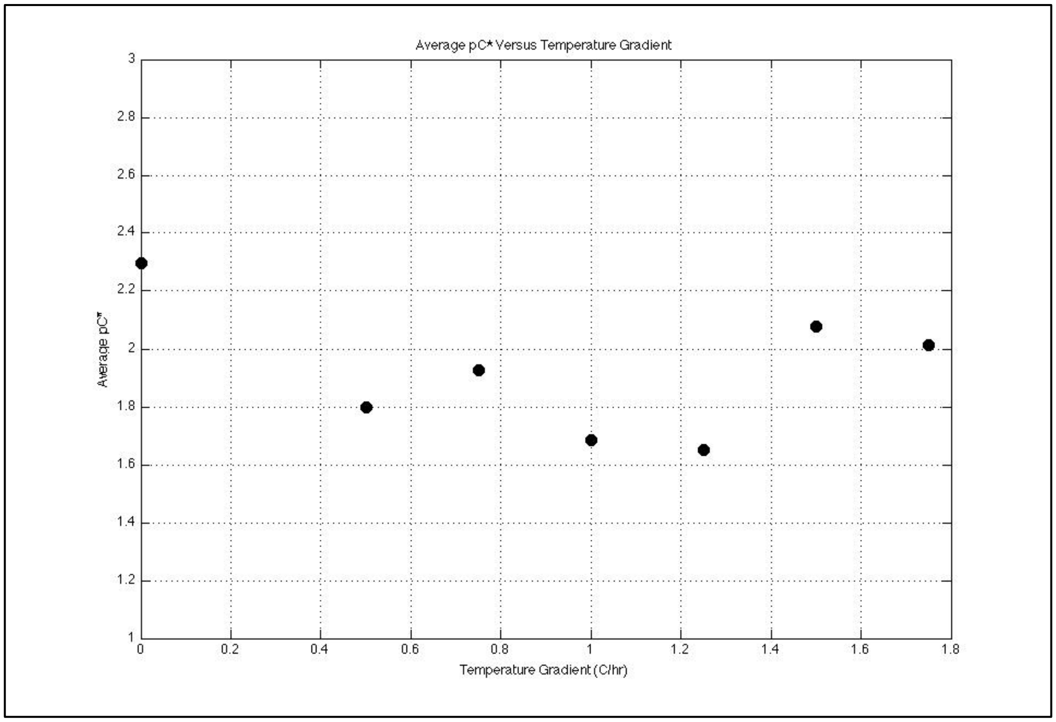

Figure 8: Averaged pC* data plotted against Temperature Gradient

The last two gradients, 1.5°C/hr and 1.75°C/hr perform better than the previous gradients; we hypothesize that this is because a different coagulant feed line was used for these runs, giving better flocculation (easily noticed during the runs with big, fluffy flocs) due to better coagulant delivery. If these two points are removed, a linear trend with an R^2 of 0.82 is found in the data, with a trend given by

$$pC^* = 2.2188 - 0.4956\, C_{grad} \text{ (with } C_{grad} \text{ in °C/hr)} . \qquad \text{(Eq. 10)}$$

While the actual coefficients are physically meaningless, they do provide some predictive ability for the specific set-up, and more importantly, provide a clear indication of decreasing treatment efficiency with increasing temperature gradient.

However, when including all the data, there is no meaningful trend in the data (the seeming sinusoidal trend is physically improbable, and possibly due to the effect of experimental error). If one were to hypothesize that the different coagulant line did not affect sedimentation greatly, it could potentially instead be that the error inherent in our system's set up was greater than any possible trends in the data, i.e., any trends are masked by experimental error. Moreover, the choice to study gradients between 0.5°C/hr and

1.75°C/hr was motivated to simulate gradients found on the field, but these might not have been the best choice of experimental parameters when trying to study an unknown trend. A wider choice of gradients (say 0.5°C/hr to 4°C/hr) would show more pronounced effects with increasing gradient.

Thus, though our experiment cannot confirm a definite relationship between increasing temperature gradients and sedimentation efficiency, it does conclusively show that performance when there is no temperature gradient is better than when there is a gradient, i.e., when the settler fails as hypothesized (of course, with the panacea that only one trial of each run was carried out).

5.5 Visual Observations

Visual observations of the tube settler confirm this conclusion as well. When there was no temperature gradient, flocs settled to the bottom of the tube settler as expected and rolled along the bottom as an avalanche when flocs built up. Dye injections showed the dye mixing through the cross section of the tube settler within a centimeter of entering it, showing no flow separation.

However, when a temperature gradient was set up in the input water, a circulation current formed in the tube settler, with warmer input water separating towards the top of the settler, and colder water returning to the bottom. Two distinct laminar layers were thus visible in the settler, one moving upwards, and one returning downwards, with very little mixing between. This circulation current affected floc settling greatly. Flocs were preferentially carried in the warmer water. While bigger flocs were still able to settle out, smaller flocs settled through the warmer water, but on reaching the denser, colder stream, floated along it and could not completely settle out, finally exiting out of the end of the tube settler. The colder water stream also disrupted the settling on the bottom of the tube settler, making it behave more as a 'conveyer belt' carrying flocs down. Dye injections showed better visualizations of this behavior, with the dye preferentially being carried into the warmer layer at the top of the tube settler and staying there (Figure 9) until its larger density caused it to settle into the bottom colder stream. This settling was delayed along the middle layer, indicating a large density difference between the cold and hot streams. (Representative videos of dye-injections have been uploaded to the YouTube Channel for AguaClara (see References), and others have been handed over to the director of the program, Professor Monroe Weber-Shirk).

Thus, bigger flocs are less affected than smaller ones. We hypothesize that bigger flocs are able to settle as they contain more clay, and the density differential might be enough to overcome the higher density of the colder water. Further, heat transfer across larger flocs might be slower (as the larger floc boundary might offer significant resistance), though we doubt that this has a large influence. Smaller flocs, on the other hand, are affected more by the density difference in the streams in the tube settler, and are the major cause for failure of the system when temperature gradients exist in the water. Building systems to capture smaller flocs or make them bigger will be important, such as the potential benefits of floc blankets to this problem.

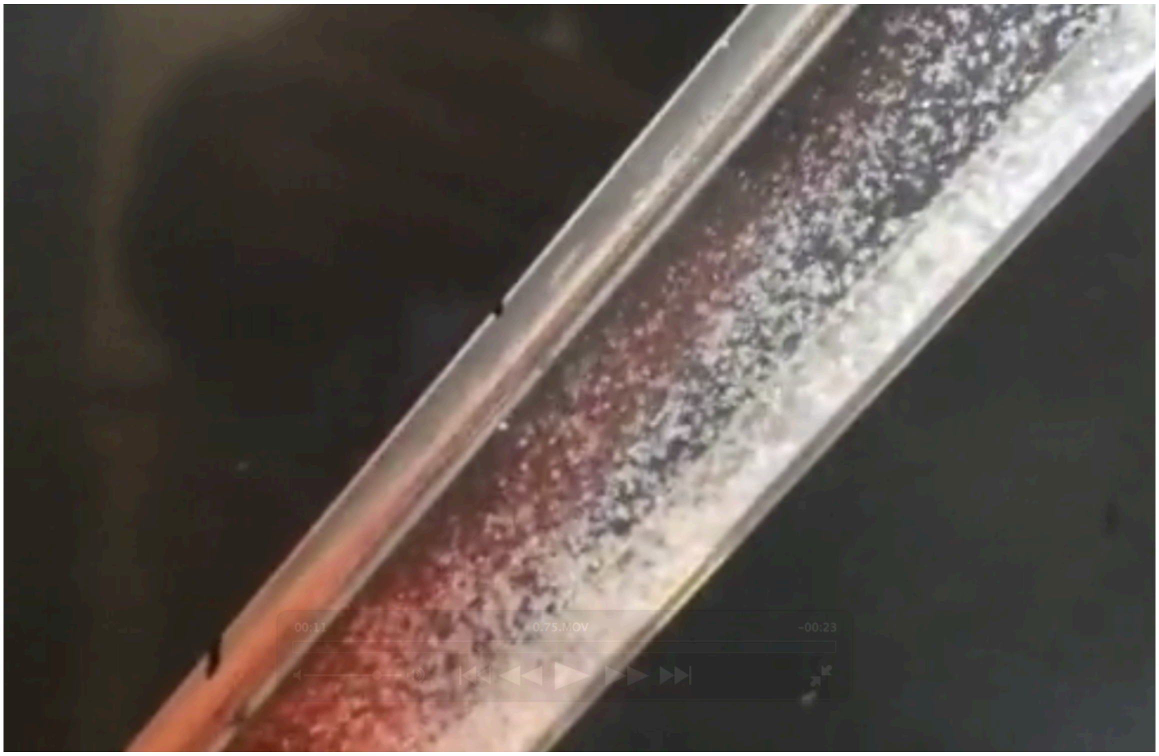

Figure 9: Flow separation in tube settler: note the dye separating into the warmer water towards the top of the settler

5.6 Suggestions for Agua Clara Plant Design

The current AguaClara plant at San Nicholas has limited options to fix the temperature gradient problem. The best possible solution is to get rid of the gradient, as our experiment has shown that even ideal tube-settlers fail when such temperature gradients are preset in influent water. The raw-water piping before plant could be buried underground instead of exposed in the air to remove or reduce the temperature gradient. It is not necessary that the entire pipeline be buried, but as long as a short portion is buried deep enough such that the water equilibrates with cooler, static ground temperature, the gradients should no longer affect water entering the plant. If this is not a possibility at the site, a reflecting, high-albedo paint could be used to paint the exposed pipe, or structures (or plants) providing shade to the pipeline could be installed.

New treatment plants that will be sourcing water that might include gradients will require an improved geometry of plate settlers, inflow and outflow in their sedimentation tank to remove or reduce the temperature gradient. Another option is to remove the temperature of the gradient in the water in the unit processes before or during sedimentation such as by re-injecting colder water from earlier in the warming day into the sedimentation/flocculation tank in order to mute the effects of temperature gradients, or by holding water in some tanks for extended periods to create batches. These fixes will require greater plant area though, as well as more involved flow control systems.

6. CONCLUSION

Our experiment has shown that tube settlers' performance is negatively affected by temperature gradients in influent raw water. Within our set up, the control performed to an average pC* of 2.3, consistently treating water to below 1 NTU while the experimental runs with a temperature gradient showed tube settler failure, with pC* dropping to 1.6 and effluent NTU rising in some cases consistently as high as 5 NTU.

While we did not find evidence for a definite trend in performance with increasing temperature gradients, this does not imply that there is no trend: deficiencies in experimental control could be masking out trends, and the small spread of independent variables we chose makes finding a trend more difficult.

Nevertheless, it was determined that circulation currents set up in the tube settler due to differing water temperature were the primary cause of failure, with small flocs unable to settle out due to the greater density of the colder stream in the tube settler. While large flocs settle out in spite of the gradient, these small flocs eventually exit the tube settler, causing high effluent turbidities. Future studies must look at a wider range of temperature gradients, and must also explore floc-scale fluid behavior to fully understand why some larger flocs are less affected by temperature gradients. Design-based experiments should also explore the position of exits and the entire geometry of tube/plate settlers.

The best possible fix for the Agua Clara plants in San Nicolas, Honduras, as of now is to remove the gradient in influent water, either by burying a section of the piping, coating it with heat (mainly radiation) resistant paint or by some other method. For new plants, redesigning the sedimentation tank and plate-settler array to account for circulation currents set up by the gradient is an important task that requires much further work.

7. FURTHER SUGESSTIONS

7.1: Future Work

There are several lines of research arising from this work that could be pursued. A larger range of gradients could be tested to explore the presence of a trend that was masked in our experimental apparatus due to error. Studies that explore the scaling of our system to plant-scale tanks should also be undertaken.

In terms of experimental design, a sedimentation tank could be added before the tube settler to observe the change in flow dynamics; this would further simulate AguaClara plants, as we ignored the floc-blanket portion of the tanks. Locations of the exit and geometry of the tube settler could also be further explored. For example, the exit could be moved to the top or bottom of the tube settler and the angle of inclination could be varied to explore the differing strength of circulation created (though this would affect sedimentation velocities). Further, the optimum coagulant dosage could also be explored, as from our observations, bigger flocs seemed to be less affected by temperature gradients. Finally, floc-scale fluid/heat-transfer behavior in the tube settler could be modeled to pinpoint the reason for tube settler failure.

7.2: Notes on Experimental Set-up for future teams

Teams working with our apparatus over the coming summer and later could make improvements to our set up to better control the experimental parameters. The addition of process controller mediated raw water NTU control and coagulant dosage are necessary to the set up; a constant head tank for (clean) raw water and a clay and coagulant stock should be used, instead of our mixed tanks.

Other things to note about the apparatus include flocculator and raw water tank integrity. It is essential that there is no air in the flocculator; we struggled with this initially. A good way to keep air out is to fill the flocculator tubing with water before coiling it around the support-cylinders. Secondly, the micro tubing for the coagulant leaked twice and we fixed it with silicone. The micro-tubing used clogs easily, thus care should be taken in its set-up. Thirdly, we observed that air was pumped into the system when the water level in the raw water tank was low, and mixing pulled air into the influent piping. Our solution was to refill the raw water tank every half an hour and keep the water level high. A better solution is using a constant head tank, controlled using Process Controller. We also found mixing dynamics in the heating tank to be poor, as the water was only mixed when the heater was turned on periodically by process control. The addition of an extra stir plate to ensure uniform temperature in the water bath fixed this problem, and later teams should be careful to ensure a well-mixed water-bath.

8. REFERENCES

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APPENDIX 1: MATLAB CODE

```
%inputting raw data from Excel
%1st entry in 'raw' is the control (0 degree gradient), then 0.5 and follow in
%increments of 0.25

% import raw data
raw = cell(7,1);

e = '.csv';
s = 'grad_';
for n = 0:numel(raw)-2
    x = 0.5+n*0.25;
    name = [s, num2str(x),e];
    raw{n+2} = csvread(name);
end

name = [s,'0',e];
raw{1} = csvread(name);

%remove -999 values in effluent and influent turbididty, and create a
%moving average of effluent NTU
data = cell(7,1);
average = cell(7,1);
sorted_NTU = cell(7,1);

res = 7*60/5; %Residence time in tube settler -for data averaging
%careful that res is even

%each entry in data has 1.time 2.actual temp (C) 3.temp ramp (C) 4.influent turb (NTU) 5.
%effluent turb (NTU)

for n =1:numel(data)
    rawm = raw{n}; %create matrix to speed memory acces in loop
    datam = NaN(numel(raw(n)),1);

    t_start = rawm(1,1);

    if n == 2 || n== 7
        r_s = 1;
        r_end = 3600*4/5;
    elseif n == 5
        r_s = 3600/5;
        r_end = 3600;
    else
        r_s = 1;
        r_end = 3600;
    end

    for r = r_s:r_end
        datam(r,1)=(rawm(r,1) - t_start)*24; %convert time to begin at 0 hr
        datam(r,2) = rawm(r,2); %actual temp
        datam(r,3) = rawm(r,4); %temp ramp

        if rawm(r,8) == -999 && rawm(r,9) ~= -999
            datam(r,4) = NaN; %influent NTU
```

```
            datam(r,5) = rawm(r,9); %efflunet NTU

        elseif rawm(r,9) == -999 && rawm(r,8) ~= -999
            datam(r,4) = rawm(r,8); %influent NTU
            datam(r,5) = NaN; %efflunet NTU

        elseif rawm(r,9) == -999 && rawm(r,8) == -999
            datam(r,4) = NaN; %influent NTU
            datam(r,5) = NaN; %efflunet NTU

        else
            datam(r,4) = rawm(r,8); %influent NTU
            datam(r,5) = rawm(r,9); %efflunet NTU

        end
    end

    if n == 5
        data{n} = datam(3600/5:numel(datam(:,1)),:);
    else
        data{n} = datam;
    end

    %Sort by increasing effluent NTU to remove spikes (outliers)
    sorted_NTU{n}=sortrows(data{n}, 5);
    last = ceil(numel(sorted_NTU{n}(:,1))-(0.01*numel(sorted_NTU{n}(:,1))));
    %replace spikes with NaNs
    sorted_NTU{n}(:,5) = [sorted_NTU{n}(1:last,5); ...
        NaN(numel(sorted_NTU{n}(:,1))-last,1)];

    %Re-sort back by time
    data{n}= sortrows(sorted_NTU{n}, 1);

    %Create a moving average of the data
    [average_in,nsum] = nanmoving_average(data{n}(:,4),res/2,1,1);
    [average_out,nsum2] = nanmoving_average(data{n}(:,5),res/2,1,1);

    average{n} = [data{n}(:,1:3),average_in, average_out];
end

%plotting raw data
figure
plot(data{1}(:,1),data{1}(:,5),'-.k')
hold on
plot(data{2}(:,1),data{2}(:,5),'-r')
plot(data{3}(:,1),data{3}(:,5),'-b')
plot(data{4}(:,1),data{4}(:,5),'-g')
plot(data{5}(:,1),data{5}(:,5),'-k')
plot(data{6}(:,1),data{6}(:,5),'-c')
plot(data{7}(:,1),data{7}(:,5),'-m')

legend('control','0.5','0.75','1','1.25','1.5','1.75')
title('Raw data without outliers and bad flocculation data: Effluent Turbidity')
xlabel('Time (hrs)')
ylabel('Effluent Turbididty (NTU)')

%plotting moving averages
```

```
plot(average{1}(:,1),average{1}(:,5),'-.k')
hold on
plot(average{2}(:,1),average{2}(:,5),'-r')
plot(average{3}(:,1),average{3}(:,5),'-b')
plot(average{4}(:,1),average{4}(:,5),'-g')
plot(average{5}(:,1),average{5}(:,5),'-k')
plot(average{6}(:,1),average{6}(:,5),'-c')
plot(average{7}(:,1),average{7}(:,5),'-m')

legend('control','0.5','0.75','1','1.25','1.5','1.75')
title('Smoothed Data: Effluent Turbidity')
xlabel('Time (hrs)')
ylabel('Effluent Turbididty (NTU)')


%%
%pC*: - log(C/C0)

res_plant = 19 + 7; %min
res_plant2 = res_plant*12;

pCstar = cell(7,1);
pCstar_ave = zeros(7,1);


for n =1:numel(data)
      count = 1;
      u=0;
      %finding the index of when t = 1.5 hr
      while u~= 1
      if average{n}(count,1) >= 1.5
         m_s = count;
         m_end = count+3600/5*1.5;
         u=1;
      else
         count=count+1;
      end
      end

      c0 = average{n}(1:(numel(average{n}(:,1))-res_plant2),4);
      c = average{n}((res_plant2+1):numel(average{n}(:,1)),5);
      pCstar{n} = -log10(c./c0);
      pCstar_ave(n) = nanmean(pCstar{n}(m_s:m_end,1));
end

%plotting graphs:
figure
plot(average{1}((res_plant2+1):numel(average{1}(:,1)),1),pCstar{1},'-.k')
hold on
plot(average{2}((res_plant2+1):numel(average{2}(:,1)),1),pCstar{2},'-r')
plot(average{3}((res_plant2+1):numel(average{3}(:,1)),1),pCstar{3},'-b')
plot(average{4}((res_plant2+1):numel(average{4}(:,1)),1),pCstar{4},'-g')
plot(average{5}((res_plant2+1):numel(average{5}(:,1)),1),pCstar{5},'-k')
plot(average{6}((res_plant2+1):numel(average{6}(:,1)),1),pCstar{6},'-c')
plot(average{7}((res_plant2+1):numel(average{7}(:,1)),1),pCstar{7},'-m')

grid on
```

```
legend('control','0.5','0.75','1','1.25','1.5','1.75','Location','SouthEast')
title('pC*, adjusted for Residence Time')
xlabel('Time (hrs)')
ylabel('pC* (- log (Turbidity_{Effluent} / Turbidity_{Influent})')


%plotting pC* against temperature gradient
grad = [0,0.5,0.75,1,1.25,1.5,1.75];
figure
plot(grad,pCstar_ave,'o','MarkerEdgeColor','k','MarkerFaceColor','k','MarkerSize',8)
grid on
ylim([1,3])
xlim([0 1.8])
title('Average pC* Versus Temperature Gradient')
xlabel('Temperature Gradient (C/hr)')
ylabel('Average pC*')

stats = regstats(pCstar_ave(1:5),grad(1:5),'linear');

% plotting temperature control
figure
plot(data{7}(:,1),data{7}(:,2),'-k')
hold on
plot(data{7}(:,1),data{7}(:,3),'-r')
plot(data{3}(:,1),data{3}(:,2),'-.k')
plot(data{3}(:,1),data{3}(:,3),'-.r')

legend('1.75 C/hr, Actual T','1.75 C/hr, Required T','0.75 C/hr, Actual T','0.75 C/hr, Required
T','Location','SouthEast')
xlabel('Time(hrs)')
ylabel('Temperature (C)')
title('Temperature Control Achieved via Process Control')

%plotting temperature control, graph 2
figure
subplot(2,1,1)
plot(data{3}(1439:2160,1),data{3}(1439:2160,2),'r')
ylabel('Temperature (C)')
title('Comparing Temperature and Effluent Turbididty, 0.75 C/hr Gradient')
xlim([2 3])
grid on

subplot(2,1,2)
plot(data{3}(1439:2160,1),data{3}(1439:2160,5))
ylabel('Effluent Turbidity (NTU)')
xlabel('Time (hrs)')
xlim([2 3])
grid on
```