Uncovering the mysteries of the floc blanket: an exploration with inlet jets, flocculators, and polyaluminum chloride precipitates

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UNCOVERING THE MYSTERIES OF THE FLOC BLANKET: AN EXPLORATION WITH INLET JETS, FLOCCULATORS, AND POLYALUMINUM CHLORIDE PRECIPITATES

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Floc blankets are used in water treatment plants to improve plant performance and aid in sludge removal and consolidation. Maintaining a fully functioning floc blanket in sedimentation tanks requires that the floc blanket remain fluidized and sludge prevented from building up on the bottom of the tank. A laboratory water treatment system was used to evaluate the range of energy dissipation rates (EDR) of the inlet to the sedimentation tank to determine when the settled effluent turbidity of the system would exceed drinking water quality standards. Increasing the inlet jet EDR up to approximately 300 mW/kg did not increase effluent turbidity of the system. Small inlet jets with high EDR can be used to ensure resuspension of the floc density current without adversely affecting water treatment plant performance.

The design of flocculators is based on mean shear (G) and hydraulic residence time (θ) and the product ($G\theta$). Guidelines for these values are conservative and designs outside the suggested range could lower plant capital costs. The following flocculator parameters were evaluated: 1) increasing G (range of 74-251 s^{-1}) while decreasing θ from 269 to 80 s (maintaining a constant $G\theta$) and 2) maintaining a

constant G (72 s^{-1}) and varying θ (24 to 1425 s). Flocculator θ below recommended design guidelines performed well indicating that shorter flocculators could be used in the presence of floc blankets.

Three potential hypotheses by which residual particles aggregate with other flocs in the floc blanket were considered: residual particles aggregate with 1) other residual particles, 2) small flocs (transitional), or 3) large flocs (hindered). Three coagulant doses (0.625, 1.25, and 2.5 mg/L) were tested with four hydraulic flocculators with constant $G\theta$ but varying G (72, 126, 251, and 340 s^{-1}) and θ (269, 159, 102, and 59 s) on the combined system. A classification system of flocs in the floc blanket was defined based on floc size and time-scale. Results strongly suggest that hypothesis 2 is valid, however, research is needed on floc sizes at specific locations within the system.

BIOGRAPHICAL SKETCH

Casey Garland grew up in a quiet mill-town in the mountains of North Carolina. She was a short-tempered yet very responsible child who liked spending time outside climbing trees. After graduating high school in 2006, Casey ventured off to North Carolina State University where she earned a Bachelor's in Biological and Agricultural Engineering in 2010. With an interest in helping people get access to clean water in developing countries, she sought out available opportunities in graduate school. Entering Cornell University in 2010, Casey thought she would only be there for two years to get at Master's in Biological and Environmental Engineering. However, after discovering the AguaClara program, she decided to pursue a Ph.D. through the program.

Per her mother, Casey has always been a bit adventurous. Trips to foreign countries, riding a motorcycle, playing rugby, and the occasional cage match have fed Casey's need for thrill through the years. However, as she gets older, the need for a thrill is satisfied by staying up past midnight. Among Casey's lesser known skills are her ability to select perfectly sized container for leftovers. This skill prevents her from having to clean more dishes and maximizes the space in her refrigerator giving her more time to drink coffee and more room for food.

This dissertation is dedicated to my mother, Sandra Garland. Through her love and actions, she has shown me what it looks like to persevere well and to see every aspect of life as a gift from God.

ACKNOWLEDGMENTS

This work was made possible through the support of the National Science Foundation.

Dr. Monroe Weber-Shirk and Dr. Len Lion: Together, you two have tirelessly worked to guide this research. Your unending curiosity and patience were a great asset to my development as a researcher.

Michelle Tong: I am so grateful for the years we spent at Cornell. Our dinners and coffees together never ceased to be a joy.

Cristina Fernandez-Baca: You were the best companion I could've asked for these last five years. Thank for all the coffee breaks and afternoon chats!

Paul Charles: You always had excellent solutions and suggests for improvement. I'll miss our conversations!

Fellow students and labmates: There's too many of you to name! Through the years, I was privileged to work (and goof around with) so many wonderful people with brilliant minds. Thank you for all you've done for me and AguaClara!

Holy Apostles: My second family! You have supported me immensely these few years and I will miss you all dearly.

My family: Mom, Dad, Clay, Rachel, Claire, Paps, Grams, Katz family - no matter what new venture I've embarked on, you've loved and supported me through them all. I hope you don't mind I added some extra letters to my name…

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1. INTRODUCTION

AguaClara is a program within Civil and Environmental Engineering at Cornell University that researches and designs water treatment facilities for developing countries. AguaClara takes conventional water treatment plant processes (flocculation, sedimentation, and filtration) and makes them more efficient and viable in communities that lack consistent electricity and material resources.

The Environmental Protection Agency (EPA) provides drinking water quality standards for many contaminants for the United States. One of these, turbidity, describes the opaqueness of the water and is measured in this research by the intensity of light scattered by a beam as collected at a 90° angle reported in Nephelometric Turbidity Units (NTU)[1]. It quantifies the contaminants in water that scatter and absorb light (suspended solids, bacteria, etc.). The turbidity standard for drinking water set by the EPA (for 95% of all samples in a month using conventional filtration) is 0.3 NTU[2] and was adopted as the goal for AguaClara treatment facilities. Sand filters in a full-scale facility (but not included in this research) will provide an additional 90% turbidity reduction beyond that achieved by sedimentation, therefore, good system performance for the system in this dissertation is defined as when the settled turbidity leaving the system (effluent turbidity) is below 3 NTU.

[1] US EPA. 1993. "Method 180.1 Determination of Turbidity by Nephelometry." Retrieved from https://www.epa.gov/sites/production/files/2015-08/documents/method_180-1_1993.pdf.

[2] US EPA. 2002. "Long Term 1 Enhanced Surface Water Treatment Rule" (40 CFR 141.500-141.571). Retrieved from https://www.gpo.gov/fdsys/pkg/FR-2002-01-14/pdf/02-409.pdf.

Depending on the characteristics of the source water to be treated, a water treatment plant will include a variety of treatment processes. In general, most plants provide conventional treatment: coagulation, flocculation, sedimentation, filtration and chlorination. When water enters a plant, it is mixed with a coagulant that coats particles and provides a 'stickiness' that enhances particle aggregation. Water is then hydrodynamically mixed to induce particle collisions (flocculation) resulting in particle aggregates called 'flocs'. Flocs are readily removed from suspension in subsequent physical separation processes of sedimentation and filtration. Flocculators (entities designed to provide flocculation) are generally designed based on three parameters: velocity gradient (G), hydraulic residence time (θ), and the product of the two ($G\theta$), also called the Camp number.

Flocculated water is sent to a sedimentation tank where physical separation processes and additional particle aggregation processes are occurring. In vertical flow sedimentation tanks, water is sent upward through the sedimentation tank at a design upflow velocity and flocs with a Stokes' setting velocity at or greater than the upflow velocity are retained in the sedimentation tank. The upflow velocity of the sedimentation tank is also referred to as the capture velocity of the sedimentation tank as retained flocs have been captured based on the set upflow velocity. Over time, as flocs are captured by the sedimentation tank, a fluidized bed of flocs (or floc blanket) forms in the lower portion of the sedimentation tank. The floc blanket provides additional reduction in residual turbidity by providing additional particle collisions. The floc blanket will increase in height over time with the addition of flocs until the top of the floc blanket reaches the floc weir. At this point, floc blanket flocs waste into the floc hopper where they are consolidated. The plant operator then periodically drains the floc hopper as it becomes full by simply opening a valve to drain the consolidated sludge. The bottom geometry of the sedimentation tank is designed such that all flocs that settle on the bottom of the sedimentation form a density current, slide down the slope of the tank, and get resuspended into the floc blanket by the inlet jet (Figure 1). Since all flocs that settle in the sedimentation tank are resuspended and the floc blanket continually wastes in the floc hopper, this design of the sedimentation tank does not need to be cleaned. This self-cleaning aspect of the sedimentation tank eliminates the down time and water wasted typically required for a sedimentation tank to be cleaned.

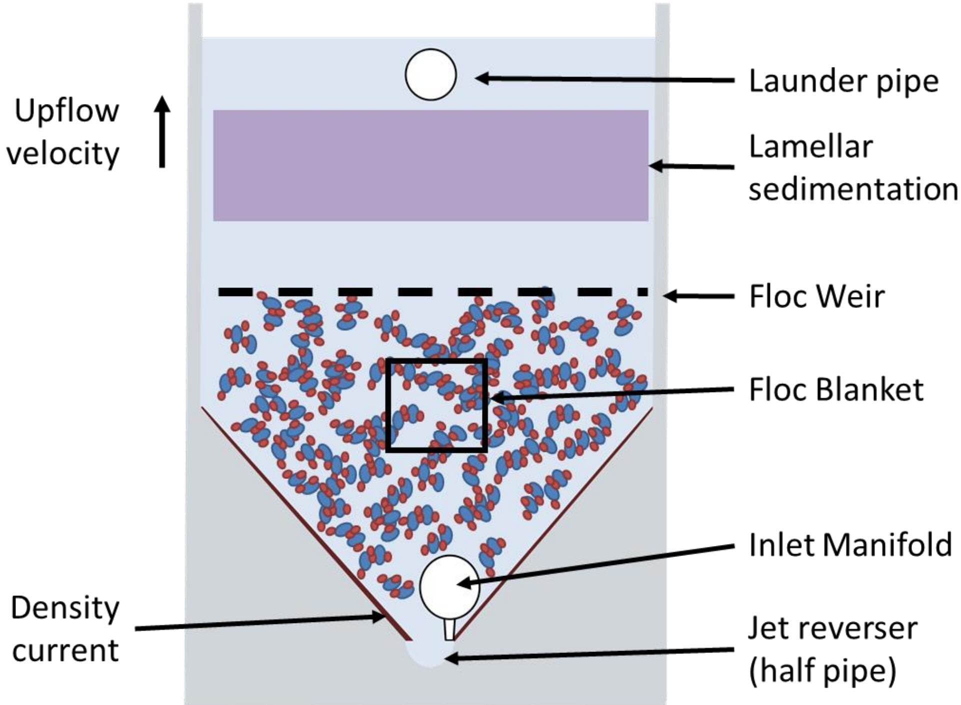

Figure 1. Side view of sedimentation tank with floc blanket, lamellar sedimentation, and inlet geometry features.

At the top of the sedimentation tank, there is another separation process called lamellar sedimentation. Inclined surfaces, usually in the form of plates or tubes, increase the surface area onto which a floc can settle and decrease the distance a particle must settle to be removed from the bulk fluid. The spacing between surfaces, inclination angle, and length of surface are selected such that flocs at and above a selected 'capture' velocity will settle onto the surface and slide back into the sedimentation tank above the floc blanket where they may reenter the floc blanket suspension. After water has passed through lamellar sedimentation, it is removed via launder pipe and sent to a sand filter where particles are further removed via adsorption and entrapment between sand particles.

Most research on water treatment processes considers individual processes and not the combined performance of all processes used. There is a general lack of understanding not only of individual processes but also of how each process influences subsequent processes. For example, it is uncertain how the floc size distribution exiting a flocculator impacts the performance of a floc blanket. A systems approach to water treatment design is needed to optimize performance and cost so that they are more viable not only for developing contexts, but also for developed contexts to reduce costs. The process that has received little attention but has great potential to reduce effluent turbidity without significant cost is the floc blanket. Floc blankets reduce residual turbidity and support a sludge consolidation method that makes the sedimentation tank self-cleaning. The research presented in this dissertation aimed to provide insights into the mechanisms controlling removal of residual turbidity by the floc blanket and provide insights that may enhance plant performance with a floc blanket.

For all the research conducted in this dissertation, a lab based water treatment system consisting of a flocculator, floc blanket, and tube settlers was used to evaluate parameters related to water treatment plant design (discussed in Chapters 2 and 3) and collisions that reduce residual turbidity in the floc blanket (Chapter 4). In Chapter 2, inlet jet velocity design of the sedimentation tank was considered. An important feature of the sedimentation tank in AguaClara designs is that the inlet jet be able resuspend settled sludge to support self-cleaning. The inlet jet must also not deteriorate effluent turbidity by breaking flocs. Therefore, the inlet jet velocity was evaluated to determine the range over which the system could be operated without failing. The two possibilities for failure were 1) effluent turbidity exceeded drinking water quality standards or 2) the inlet jet was unable to resuspend the density current created by settled flocs on the hopper bottom and, therefore, could not support the self-cleaning aspect of the floc blanket. Chapter 3 considers recommended design guidelines for flocculators and examines how flocculator design can impact system performance in the presence of a floc blanket. Seven different flocculators with varying velocity gradient (G) and hydraulic residence time (θ) were tested with the flocculator, floc blanket, and tube settler system to determine how the floc blanket and system performance respond.

Chapter 4 develops and examines hypotheses of residual particle aggregation within the floc blanket. Results from experiments on the combined flocculator, floc blanket, and tube settler system with four different flocculators ($G\theta$ is kept constant while varying G and θ) and three coagulant doses are used to prove or disprove the proposed hypotheses. Research suggests that residual (non-settleable) particles are removed by colliding with small flocs within the floc blanket. These small flocs are likely consolidated by the tube settlers. Additionally, three categories of flocs based on floc size and time-scale are defined for the floc blanket.

CHAPTER 2. INFLUENCE OF VARIABLE INLET JET VELOCITY ON FAILURE MODES OF A FLOC BLANKET IN A WATER TREATMENT PROCESS TRAIN

Abstract[3]

Improving the designs of facilities that employ floc blankets in a water treatment process train to ensure stable performance is desirable, as is an understanding of suitable operating conditions to maintain a functional floc blanket in the system. By considering sequential processes when choosing design parameters, the whole system can be optimized to produce high quality effluent at low cost. A lab scale water treatment system with flocculator, floc blanket and lamellar sedimentation was used to evaluate the effect of energy dissipation rates (EDR) in the inlet jet to the floc blanket on performance of the system as a whole. Results show that the presence of a floc blanket provided an additional factor of 8 decrease in settled water suspended solids concentration at an upflow velocity 1.2 mm/s. Inlet jet EDR did not impact system performance until approximately 300 mW/kg after which the settled water turbidity increased. At the lower end of inlet jet EDR tested, the jet was unable to resuspend settled flocs. Given that plant performance was acceptable at higher inlet jet energy dissipation rates, smaller inlet jets with a higher velocity could be used to ensure resuspension of flocs for continuous hydraulic cleaning.

Introduction

Numerous books and journal articles have been published on water treatment

[3] The contents of this chapter have been published in *Environmental Engineering Science* with co-authors M.L. Weber-Shirk and L.W. Lion.

facility design. Many of them provide guidelines for velocities, residence times and other relevant design parameters that are primarily based on studies of individual unit processes. Optimizing the design of a water treatment facility as an interconnected series of processes to balance performance and cost has not yet been possible because of an incomplete understanding of the interactions between unit processes. It is possible that many design parameters would change if the sequence of individual processes were optimized as a whole to reduce cost and produce the target treated water quality.

Floc blankets are fluidized beds of flocculating particles (flocs) that are created under upflow (as opposed to horizontal flow) conditions in a sedimentation basin. Ideal sedimentation tanks should provide efficient particle removal to achieve long runtimes for downstream filters while minimizing downtime for cleaning of the sedimentation tank. Floc blankets can provide improved particle removal without increasing the size of a sedimentation tank. Floc blankets have the added benefits of

- hydraulically eliminating sludge from the sedimentation tank without any moving parts
- reducing biologically mediated gas production from settled solids
- dissipating the momentum of the influent water and producing uniform vertical fluid velocities entering overlying plate settlers
- enabling the construction of sedimentation basins that are less than 2 m deep.

Enhanced colloid capture in a floc blanket has been attributed to colloidal attachment to suspended flocs (Edzwald, 2011; Binnie and Kimber, 2013); however, the specific removal mechanisms have not been resolved. Sustained operation of a flocculation/sedimentation treatment train with a floc blanket requires an understanding of conditions that may result in floc blanket failure and the ensuing high turbidity effluent. Failure to adequately operate a floc blanket is linked to pathogenic outbreaks (Logsdon, 2006). Therefore, improving the designs of water treatment facilities that employ floc blankets in the process train to ensure stable performance is desirable, as is an understanding of suitable operating conditions.

AguaClara is a program at Cornell University that researches, invents, and designs ultra-low energy (15 J/L) municipal water treatment facilities that operate without the use of electricity. Sedimentation tanks designed by AguaClara (http://aguaclara.cornell.edu/implementation/design/) employ a sloped-bottom design that injects water into the bottom of the tank through a manifold that creates a line jet (Figure 2). The sloped bottom allows settled flocs to form a floc density current and slide down to be resuspended by the incoming jet of flocculated water. If the momentum of the inlet jet is sufficient, the density current with a high concentration of flocs is returned to the floc blanket instead of accumulating as sludge in the bottom of the tank. This zero sludge design eliminates the need for mechanical sludge removal equipment. The AguaClara sedimentation tank can operate continuously by wasting excess floc blanket solids across a floc weir into a floc hopper. The floc hopper is drained periodically or continuously (while the sedimentation tank is still running) to remove consolidated solids.

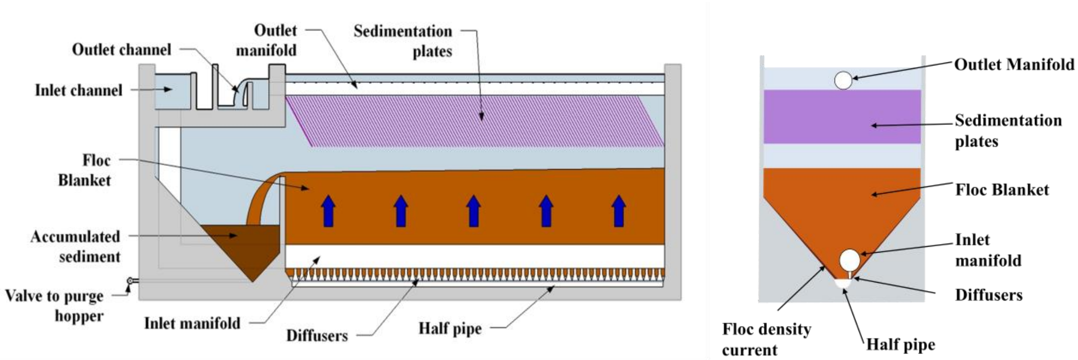

Figure 2. Schematic (front and side view) of the AguaClara Sedimentation Tank Design.

Residence time, velocity through conduits, upflow velocity (surface loading rate) and velocity gradient are key parameters used for water treatment facility design. For conditions of turbulent flow, the energy dissipation rate (EDR) is a parameter that controls the floc aggregation rate and the maximum floc size (Cleasby, 1984). Evidence from tests of coupled flocculation, sedimentation systems is often lacking to justify suggested design parameters. It is not clear how individual processes can be modified to optimize the whole treatment process sequence. The 10 State Standards suggest avoiding an increase in velocity and velocity gradient between flocculation and sedimentation basins (*Recommended Standards for Water Works*, 2012) presumably to avoid breakup of flocs. In some sedimentation tank designs the inlet consists of a manifold of relatively small diameter orifices. If velocity is held constant, the energy dissipation rate increases as the relevant length scale of the flow decreases (see Equation (1) adapted from Baldyga et al., 1995 and maintaining the same EDR as was used in the flocculator would require lower velocities in the inlet jets than in the flocculator. The energy dissipation rate of the jet is given by:

$$\varepsilon_{Jet} = \frac{\left(\Pi_{Jet} V_{Jet}\right)^3}{D_{Jet}} \tag{1}$$

Where ε_{Jet} is the energy dissipation rate (mW/kg of fluid mass), Π_{Jet} = experimental coefficient dependent on jet parameters (round, plane, bounded, etc.), V_{Jet} is the velocity of the jet (m/s), and D_{Jet} is the diameter of the jet. According to the results compiled by Baldyga et al., 1995, Π_{Jet} for an axisymmetric jet has a value of approximately 0.5.

Other design guidelines and research suggest that use of higher EDR (a parameter closely related to the velocity gradient that describes the intensity of mixing) to create small, dense flocs would enhance removal in systems with direct filtration (Edzwald, 2011; Binnie and Kimber, 2013; Bache and Gregory, 2010). Therefore, conduits between flocculator and sedimentation unit processes could be smaller with high EDR without negatively impacting performance. Some studies have considered the impact of fluid shear on flocs but this parameter does not provide conclusive expectations as to whether plant performance would change. For example, if lamellar plate settlers are used above a floc blanket, flocs broken by an increase in EDR may still be large enough to be captured. Conversely, an increase in floc size does not necessarily imply an improvement in plant performance. The goal of water treatment is to produce low turbidity water, not to produce large flocs.

The design of entry conditions for flocculated suspensions into sedimentation tanks is commonly constrained to minimize breakage of flocs and, in the case of horizontal sedimentation tanks, to not scour settled sludge (Edzwald, 2011). However, resuspending settled flocs is necessary to build a floc blanket and provides a method to eliminate sludge accumulation in the sedimentation tank. Therefore, application of entry conditions suitable for horizontal sedimentation tanks to AguaClara systems or other upflow systems with floc blankets is likely not appropriate.

Biodegradation of accumulated sludge in sedimentation tanks can cause performance to worsen by releasing gaseous products that carry particles to the surface and thus elimination of settled sludge can improve particle removal efficiency. The ability of an inlet jet to resuspend the floc density current of settled flocs in an upflow sedimentation reactor with a floc blanket is dependent on the velocity of the incoming water. If settled flocs are not resuspended, the inlet jet region will fill and create a non-uniform distribution of flow. Retaining the EDR used in the flocculator in the sedimentation tank inlet jets results in much lower velocities that may not be able to resuspend the floc density current. The only specific recommendations available for inlet velocities for the sedimentation tank are for horizontal flow, flat-bottomed tanks. Since sludge will be removed by mechanical cleaners at the bottom of a horizontal sedimentation tank, design recommendations suggest an inlet jet velocity of 10 to 25 mm/s in basins 2.1 to 4.3 m deep so that settled sludge is not scoured (AWWA/ASCE, 2012).

The goal of the sloped bottom in the AguaClara sedimentation tank design is to return settled flocs to the inlet jet where they may be resuspended to facilitate rapid floc blanket growth. When the floc blanket design incorporates a floc hopper that harvests flocs at the floc water interface, excess flocs can be wasted hydraulically from the floc hopper. With flat-bottomed designs, the sedimentation tank has to be cleaned by mechanical submerged moving parts that are prone to failure or manually cleaned resulting in downtime. Design recommendations and prior research (Head et al., 1997, Sung et al., 2003, Chen et al., 2006, etc). for sedimentation tanks are confined to flat bottomed tanks. The AguaClara design seeks to maintain a continuous operation by resuspending all settled flocs and wasting the floc blanket at the floc water interface over a floc weir into a floc hopper.

One of the key parameters in the design of the AguaClara sedimentation tank is the velocity of the inlet jet and the goal of this research was to determine how this parameter influences settled effluent turbidity of a sequential flocculation, floc blanket, and lamellar sedimentation process. A range of sedimentation tank inlet jet energy dissipation rates were tested to determine the limits of failure. The hypothesis was that an increase of inlet jet EDR at the entrance to the sedimentation tank would result in floc breakup that would cause an increase in settled water turbidity at higher

EDR and that decreasing jet EDR would eventually result in a failure to resuspend flocs. Operational behavior of the floc blanket was also observed and is discussed.

Experimental Protocol

The lab scale experimental apparatus was the same as described by Hurst et al. (2014) with the exception that a floc weir was used to limit floc blanket height and almost all influent fluid was removed from the reactor by passage through tube settlers. A schematic of the apparatus is provided in Figure 3. Aerated tap water (average pH 7.36, total alkalinity 131 mg/L as $CaCO_3$, total hardness 150 mg/L as $CaCO_3$, Dissolved Organic Carbon 1.83 mg/L, Cornell University Water System, 2014) was mixed with an 8 gram/L stock kaolinite clay suspension (R.T. Vanderbilt Co., Inc. Norwalk, CT.) to form a 100 Nephelometric Turbidity Unit (NTU) synthetic raw feed water. To maintain a steady influent suspended solids concentration, an in-line turbidity meter monitored the turbidity and Proportional Integral Derivative (PID) control was used to meter the clay stock. Polyaluminum chloride (PACl) (PCH-180 Holland Co., Adams, MA) was mixed to create stocks of either 159 mg/L or 265 mg/L as Al and added to the influent stream using a peristaltic pump. The flow rate of the pump was adjusted to obtain a PACl dose of 0.9 mg/L as Al to the influent during experiments.

Flocculation was achieved by a 121 m coiled tube flocculator (tube inner diameter of 9.5 mm, coil diameter of 130 mm). The energy dissipation rate in the flocculator was calculated based on the head loss of a helically coiled tube using the

Dean number (see Tse et al., 2001). Two upflow velocities in the floc blanket were used for experiments, 1.2 and 1.6 mm/s, and were achieved by increasing the experimental flow through the flocculator. Table 1 shows hydraulic and mixing parameters in the flocculator for each upflow condition.

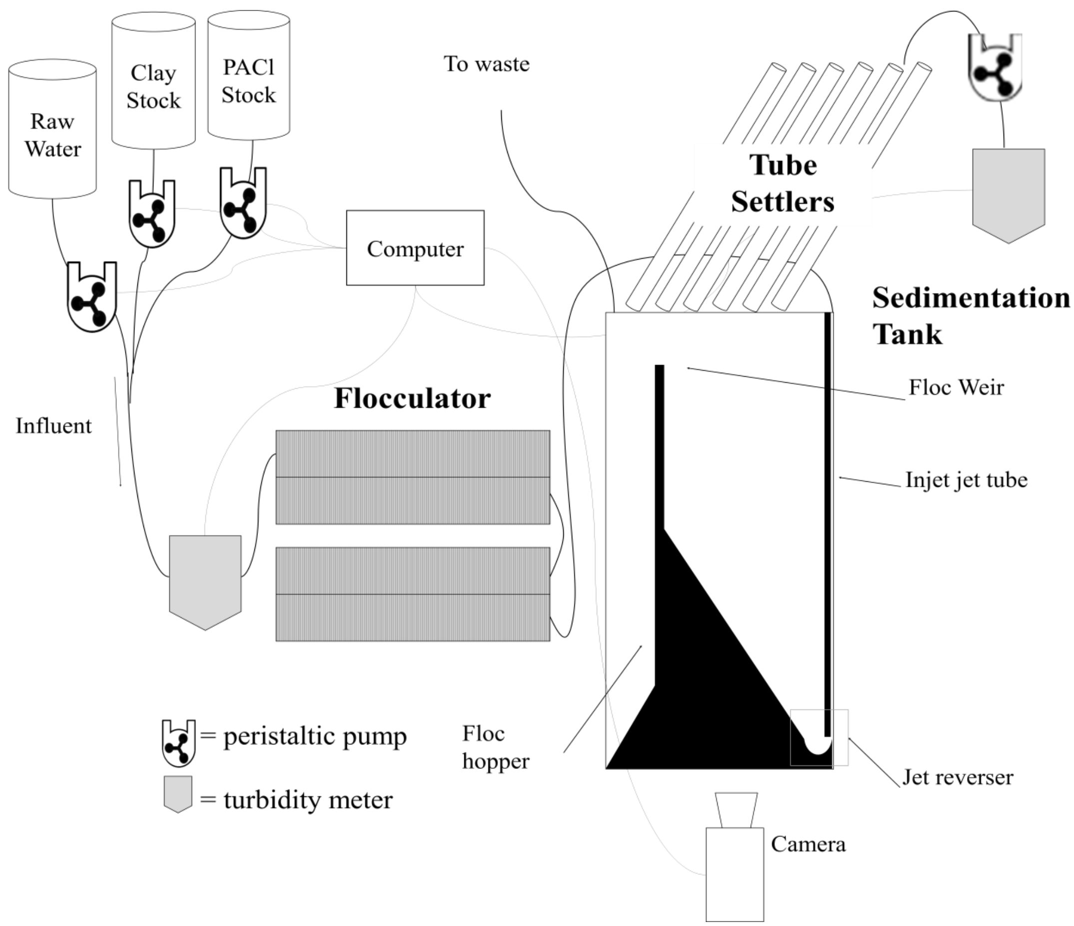

Figure 3. Design schematic of experimental apparatus. Influent to the sedimentation tank from the flocculator entered through inlet jet tubes of variable size. The downward direction of the influent flow is redirected upward by the semicircular jet reverser bottom geometry. A small percentage of the flow insufficient to supply an additional tube settler and was sent to waste.

Capture velocity (also referred to as the critical velocity) of the tube settlers was set at 0.1 mm/s for both upflow velocities; an additional tube settler was used to remove additional flow in the higher upflow velocity condition. The energy dissipation rate in the inlet portion of the sedimentation tank was changed by altering the diameter of the tube delivering flocculated water to the bottom of the tank.

Table 1. Flocculator hydraulic parameters under experiment conditions for 1.2 and 1.6 mm/s upflow velocities tested.

	Upflow Velocity (mm/s)	
	1.2	1.6
$G\theta$	96,000	101,000
Flocculator Reynold's Number*	815	1086
Flocculator head loss (m)	0.74	1.1
Flocculator average energy dissipation rate, ε (mW/kg)	4.5	8.9

*Reynolds number is for straight pipe, $Re=Vd/\nu$ (V is mean fluid velocity, d is diameter of tube, and ν is kinematic viscosity of water)

To calculate maximum EDR for the jet, Equation (1) is used and Π_{Jet} approximated to 0.225 by computational fluid dynamic simulation of 2-D jets (see Appendix for derivation). This value falls within experimental results of 0.23 for a plane, bounded jet (Haarhoff and Van Der Walt, 2001) and 0.5 for a round, free jet (Baldyga et al., 1995).

After the fluid exits the inlet jet tube, it travels around the jet reverser and begins to expand in the bottom of the tank. When the jet exits the round tube the cross section of flow is observed to be round. As the fluid travels around the jet reverser, it expands to the width of the experimental tank and the cross section of the jet appears to become a rectangle (Figure 4). When the jet exits the reverser, it appears to be a plane jet. This study did not confirm the cross-sectional areas of the jet exiting the round tube or the jet reverser. Additionally, it was assumed that flow rate and velocity are conserved so the cross-sectional area of the flow remains the same such that $A_{tube} = A_{PlaneJet}$. This should be confirmed in future studies. The smallest dimension of flow becomes the smallest dimension when the jet exits the reverser. The area of the plane jet is calculated by:

$$A_{PlaneJet} = S_{Tank} W_{Jet} \tag{2}$$

S_{Tank} is the width of the tank (12.7 mm) and W_{Jet} is the width of the jet. D_{Jet} then becomes W_{Jet} in Equation 1 and is used in jet EDR calculations.

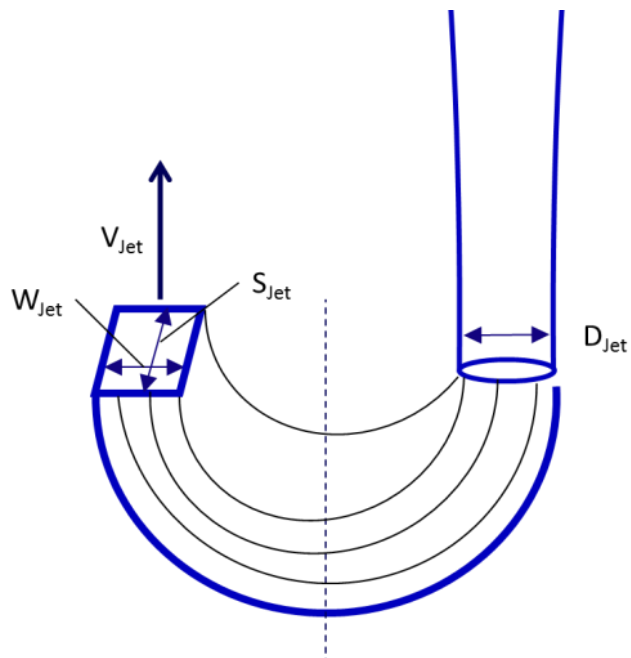

Figure 4. Diagram of changing relevant flow dimensions in the jet reverser.

The range of tube diameters tested was 2.0 to 11.7 mm which corresponded to maximum energy dissipation rates ranging from 0.25 to 337,000 mW/kg (Figure 5 using equation 1), an exit velocity that varied from 0.06 to 1.9 m/s and a calculated straight pipe head loss through the inlet jet tube of $1.6x10^{-3}$ to 8.4 m. The lowest velocity jet tested was more than double the maximum velocity recommended to prevent particle scour in horizontal sedimentation tanks (AWWA/ASCE, 2012).

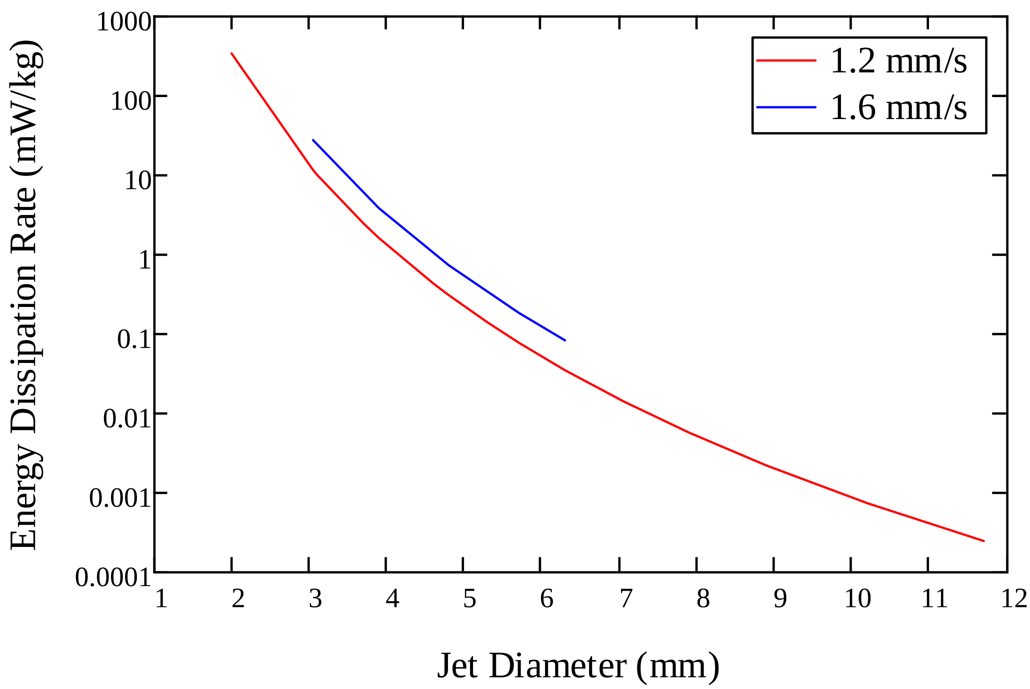

Figure 5. Calculated energy dissipation rates created by each jet diameter for upflow velocities of 1.2 and 1.6 mm/s.

Images of the floc blanket were collected every 60 seconds with a Basler (Basler, Ahrensburg, Germany) color SCA640-70FC IEEE-1394B (658 X490 pixels) using an 8 mm lens and backlight with an LED panel (Hurst et al., 2014). Effluent turbidity readings were collected at 5 second intervals for the duration of each experiment using an inline turbidity meter (HF Scientific Microtol Inline Turbidity Meter).

Visual regions of interest used for image analysis of blanket and supernatant (i.e., fluid above the floc water interface) suspended solids concentrations are shown in Figure 6 along with the region used to determine floc blanket height. Suspended solids concentrations were determined according to methods described by Hurst et al. (2014) based on absorbance of incident light.

Failure of the floc blanket tube settler system was defined as observation of an effluent turbidity in excess of 3 NTU (deemed to be an upper limit for water to be treated by filtration) or when the influent jet was unable to resuspend the floc density current coming from the sloped bottom into the jet reverser region. These failures cover conditions at the highest and lowest jet energy dissipation rates that would prevent the floc blanket sedimentation system from producing an acceptable quality of water.

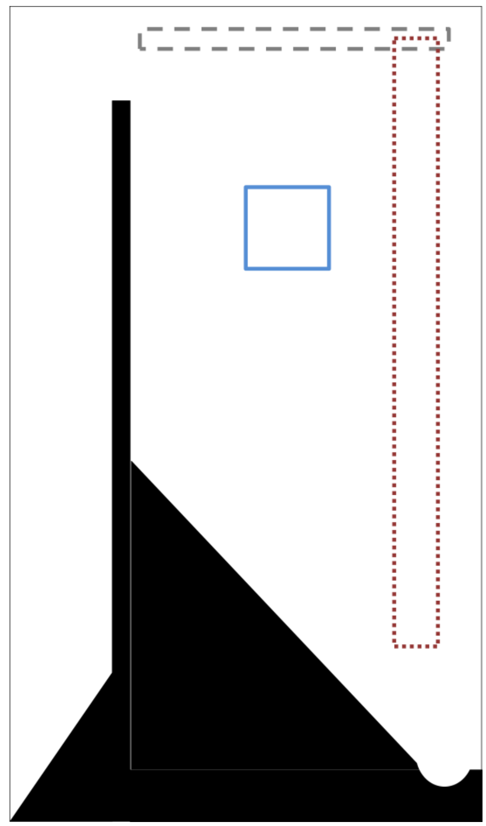

Figure 6. Regions of interest selected for image analysis of floc blanket (solid blue line), supernatant (dashed gray line), and floc blanket height (dotted red line)

System performance prior to a floc blanket was determined by extracting effluent turbidity data at one residence time of the entire system (referred to here as the experimental conditioning phase). The first full residence time of the floc blanket (calculated as the floc blanket volume divided by the system volume flow rate (44 and 37 minutes assuming plug flow for 1.2 and 1.6 mm/s upflow velocity, respectively) was required for the initial particle free water in the experimental apparatus to exit the system. This time was sufficient for the first fluid packet of flocculated water to pass through the system and reach the effluent turbidity meter. Effluent turbidity detected at this point in time was not influenced by the presence of a floc blanket.

During experimentation, the fluid exiting the inlet jet tube traveled in a semi-circular flow through the bottom geometry (referred to here as the jet reverser) and mixed with the incoming floc density current. The upward vertical momentum of the jet exiting the reverser region must be higher than the downward momentum of the incoming floc density current to prevent accumulation of flocs. The balance between the momentum of the jet and floc density current was reflected in the angle between the floc density current and the upward jet (Figure 7). As the inlet jet diameter increased (EDR decreased) and mass flow rate remained constant, jet velocity decreased causing the momentum of the incoming flow to decrease. Since momentum of the jet decreased as jet diameter increased and the floc density current did not change considerably, the downward momentum of the floc density current eventually exceeded the upward momentum of the inlet jet leading to failure. Thus, at failure there was insufficient vertical momentum to carry the settled flocs back up into the floc blanket (see Figure 7).

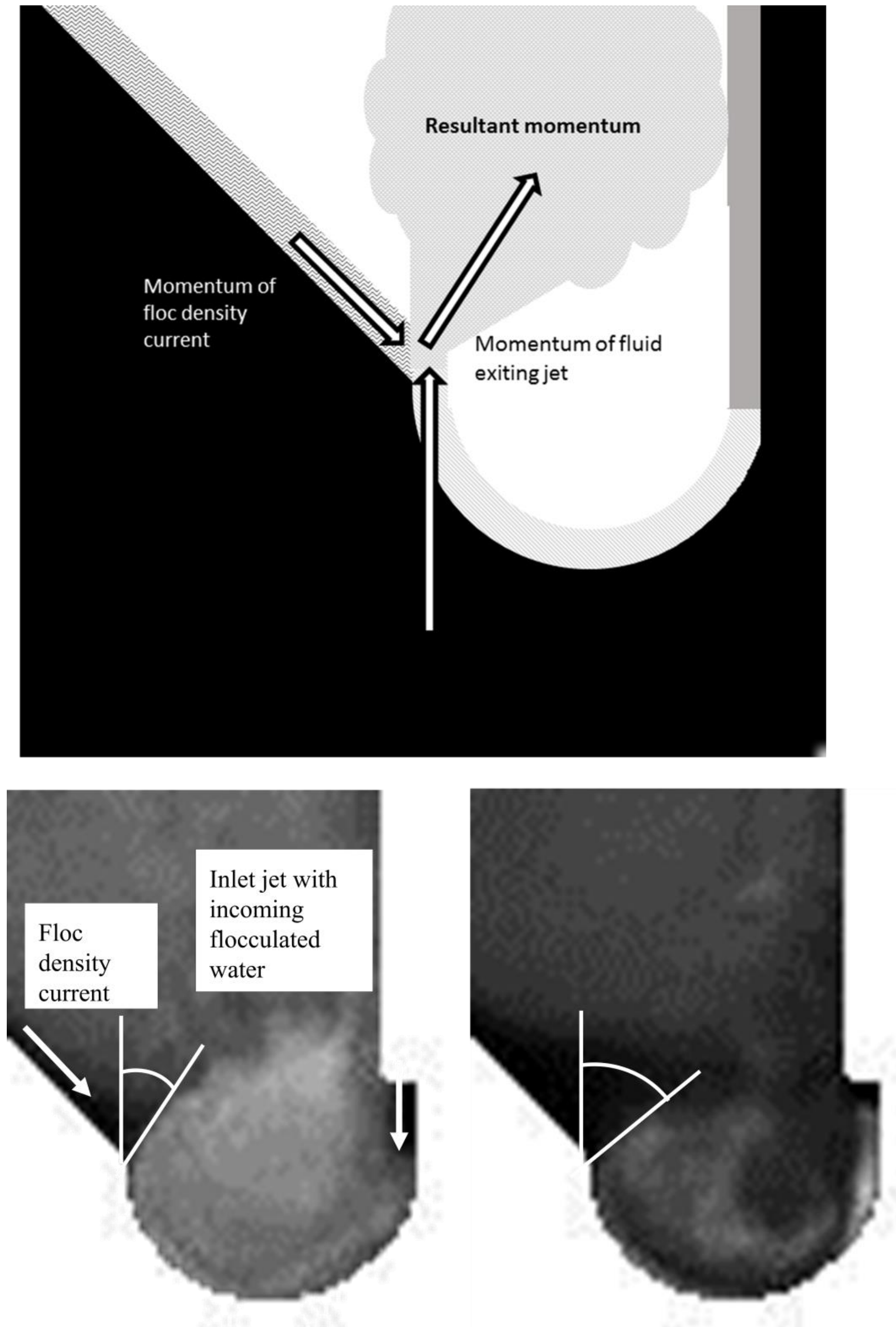

Figure 7. Close-up of the confluence of the floc density current and the upward jet at steady state for 7.05 mm (left) and 8.9 mm (right) jet diameters. The angle of jet interaction with the density current (indicated with a superimposed line) increased as the jet velocity decreased leading to failure for low momentum jets.

Results

A floc blanket formed for all experimental conditions tested. The total time required to form a blanket ranged from 3 hours at the 1.6 mm/s upflow velocity to 5 hours at the upflow velocity of 1.2 mm/s.

There were two potential failure modes of the system when changing the inlet jet EDR: (1) the effluent turbidity was greater than 3 NTU and (2) the jet was unable to resuspend the density current of settled flocs, allowing settled solids to fill in the inlet jet reverser. In the first failure mode, it is assumed that flocs were broken by the increased EDR to a size and quantity that could not be captured by the tube settlers or reformed in the floc blanket. The latter failure mode (accumulation of solids in the jet reverser region) would result in one or more of the following: uneven flow distribution in the tank because the inlet was occluded resulting in preferential flow through consolidating sludge in the jet region, and the inability for complete resuspension of settled solids needed to support continuous operation.

Blanket, Supernatant and Effluent Concentrations for Floc Blankets at Steady State

Floc blanket concentration in the sedimentation tank reached a steady value before the floc blanket reached the floc weir. Once the floc blanket developed a clear floc water interface and started growing in height, the floc blanket stayed at approximately the same suspended solids concentration for the rest of the experiment as confirmed by image analysis. The floc blanket grew to the height of the floc weir and then maintained a constant height by wasting over the floc weir.

Figure 8 provides an example run with images at times when the system is changing or at steady state. Once the system completed the conditioning phase (i.e., after one fluid residence time), the supernatant suspended solids concentration and effluent turbidity increased dramatically and then decreased as the floc water interface became apparent and the height of the floc blanket started increasing. The supernatant concentration steadily rose after the floc blanket developed and grew in height while the effluent turbidity steadily decreased. Once the floc blanket reached the floc weir and started wasting to the floc hopper, it was considered to be at steady state as the height was fixed and the floc blanket concentration remained the same.

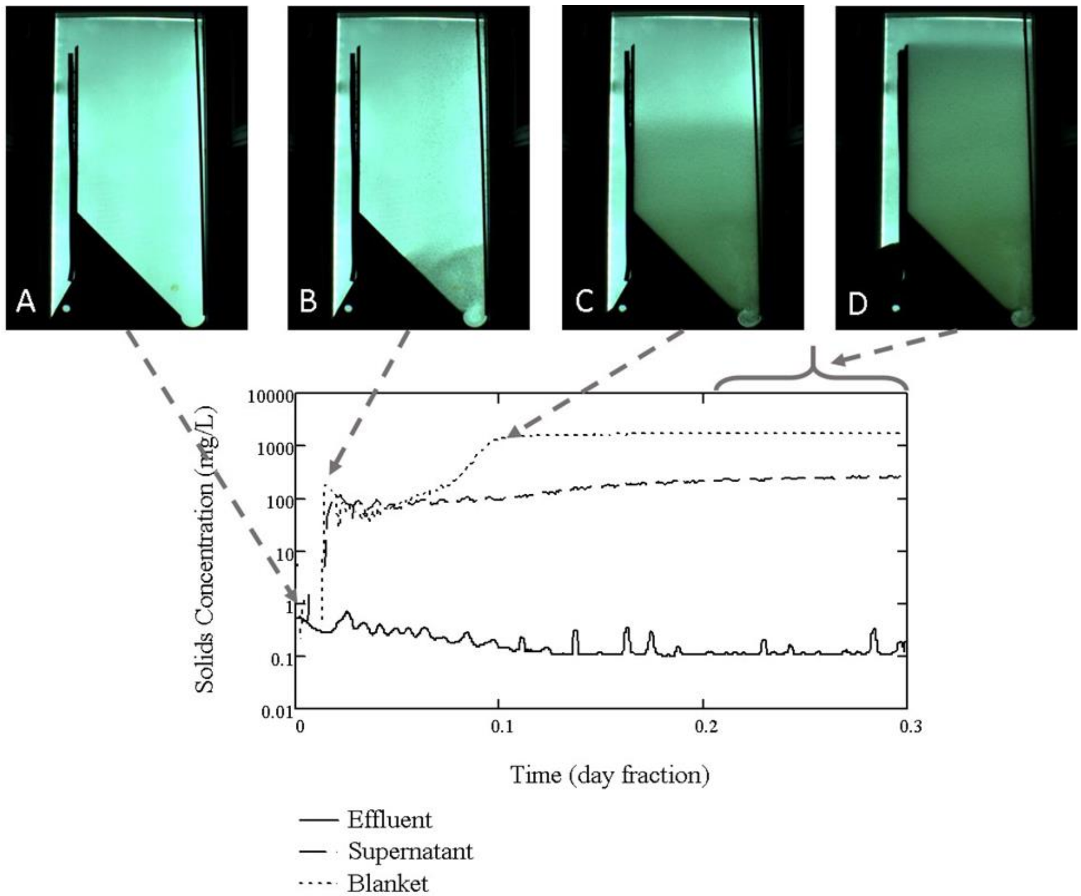

Figure 8.Example experimental run with images at notable times. Image A is just after the system is started and marks the beginning of the conditioning phase. Image B is when the conditioning phase is complete and the supernatant and effluent turbidity spike. Image C is just after the floc blanket has passed through the blanket ROI. Image D is the tank at steady state after the floc blanket has reached the floc weir.

Seasonal variations of organic matter in the source water negatively affected the coagulant resulting in higher floc blanket concentrations. Standard deviations are presented for floc blanket and supernatant concentration to indicate that concentrations were considered constant given experimental variability. For the range of EDR tested (excluding failures at the highest and lowest EDR), the average floc blanket concentration was 1,608 mg/L (σ = 294 mg/L) at the 1.2 mm/s upflow velocity and 1,145 mg/L (σ = 218 mg/L) at the 1.6 mm/s upflow velocity. Average supernatant concentrations were 193 mg/L (σ = 59 mg/L) and 159 mg/L (σ = 82 mg/L) for 1.2 and 1.6 mm/s, respectively. Average effluent turbidities were 0.74 NTU (σ = 0.67 NTU) and 0.72 NTU (σ = 0.92 NTU). Coefficients of variation for steady state floc blanket concentrations were 0.18 and 0.19 for 1.2 and 1.6 mm/s, respectively. Steady state concentrations for all locations monitored are presented in Figure 9. At the largest jet EDR tested (337,000 mW/kg for 1.2 mm/s and 27,300 mW/kg for 1.6 mm/s), the effluent turbidity was above 3 NTU resulting in system failure. The results reveal a steady increase in effluent turbidity beginning at approximately 300 mW/kg before the system reached failure. In this region after the effluent turbidity begins to increase and before failure, it is expected that some flocs were broken and system performance was adversely affected by high the EDR in the influent jet.

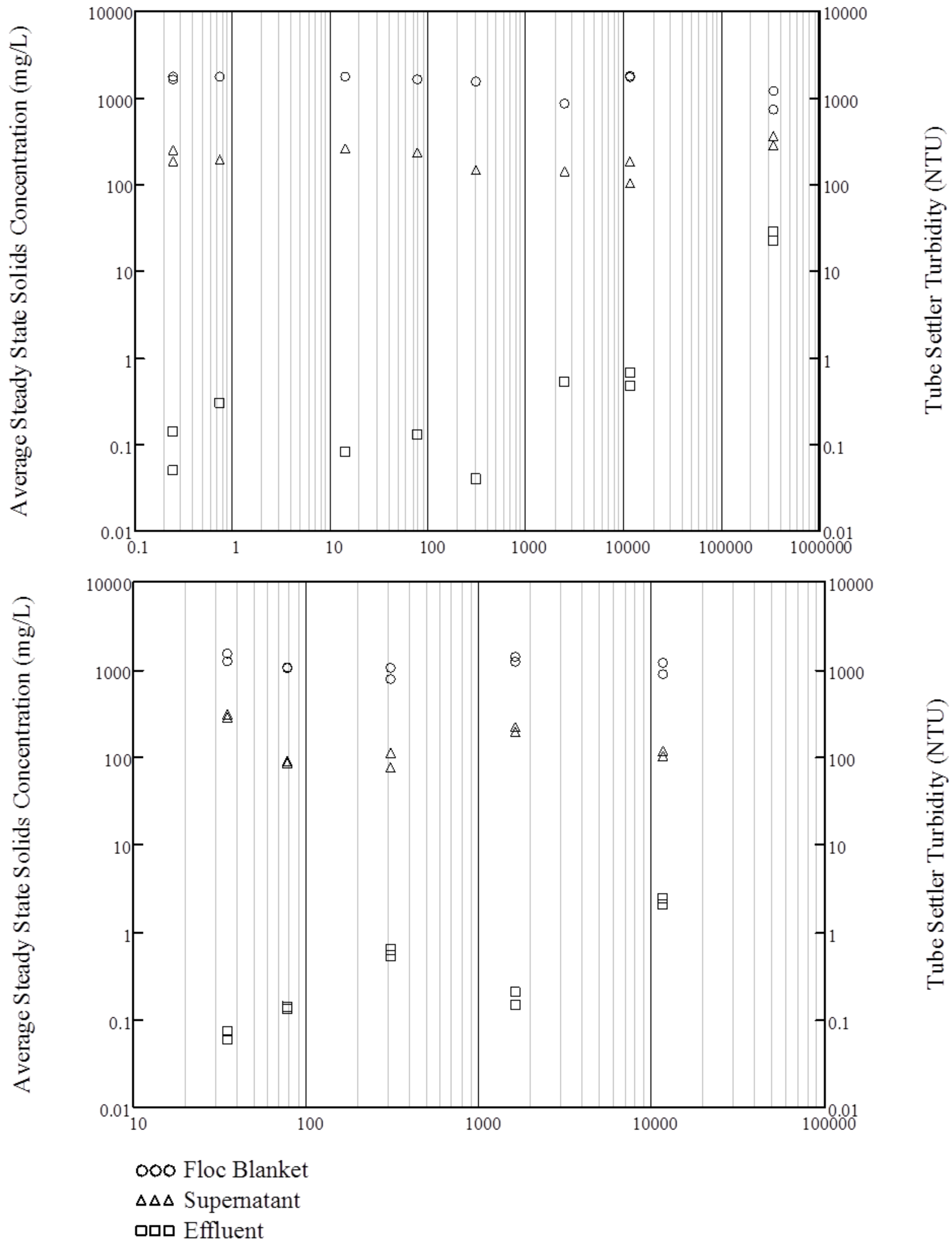

Figure 9. System suspended solids concentrations during steady state as a function of jet energy dissipation rate for 1.2 mm/s (top) and 1.6 mm/s (bottom). Results shown are averaged over 2 residence times (1200 seconds) of the sedimentation tank.

System failure occurred at the lowest EDR tested at 1.2 mm/s (0.25 mW/kg) as the jet reverser began to fill in with the floc density current. Failure to resuspend settled flocs did not occur for any EDR tested at the 1.6 mm/s upflow velocity. Figure 10 shows an example of the system when the jet reverser is adequately cleared (left photo) and when it is being filled in (right photo).

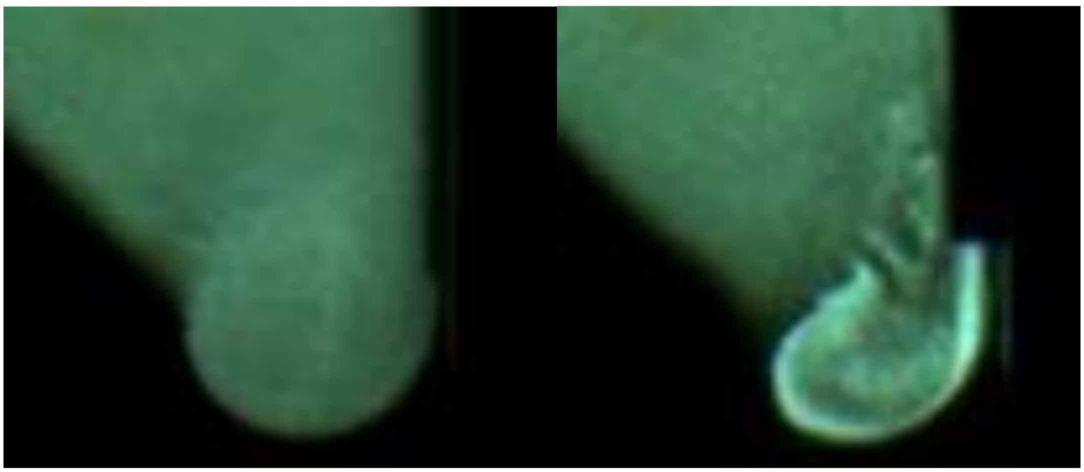

Figure 10. Close up images of the system not in failure at 2,500 mW/kg (left) and in failure as the jet reverser fills in at 0.25 mW/kg (right).

Performance with and without floc blanket

Overall floc blanket performance was defined in terms of the negative logarithm of the ratio of solids concentration in the effluent and influent (pC^*) (Equation 3). High values of pC^* correspond to improved performance.

$$pC^* = -log\left(\frac{C_{Effluent}}{C_{Influent}}\right) \quad (3)$$

In all experiments, system performance increased in the presence of a floc blanket (Figure 11 and Figure 12) however a smaller change in performance is noted at the extremes of inlet jet EDR for 1.2 mm/s. Performance with a floc blanket improved by an average of 0.9 *pC** (i.e., an 8-fold decrease in effluent turbidity) across all EDRs not in failure at an upflow velocity of 1.2 mm/s and 0.4 *pC** (2.5-fold decrease in effluent turbidity) for 1.6 mm/s upflow velocity.

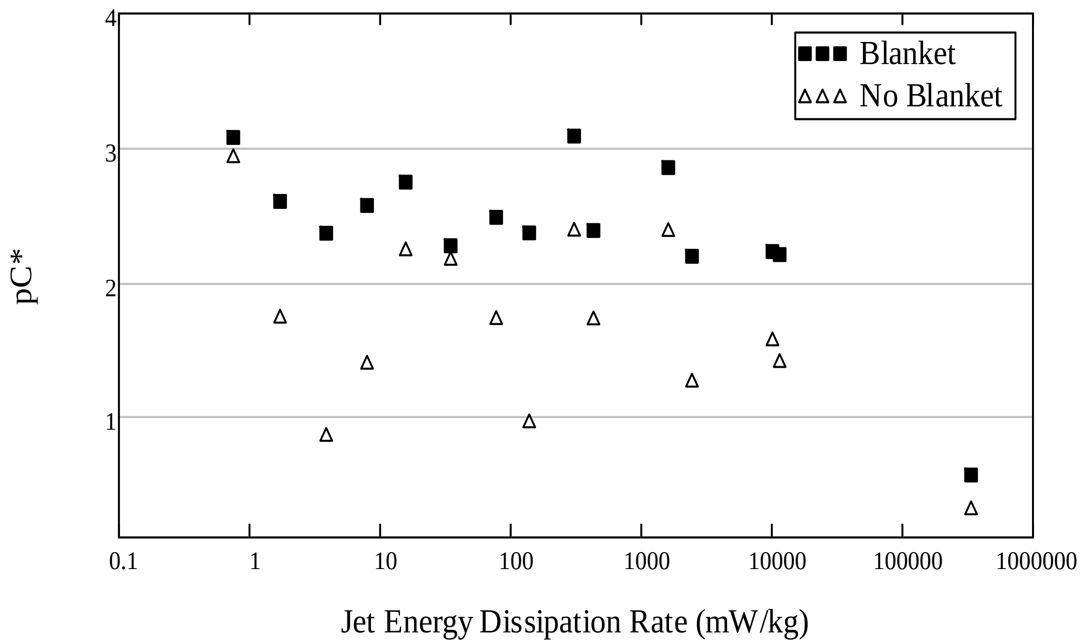

Figure 11. System performance with and without floc blanket at upflow velocity of 1.2 mm/s.

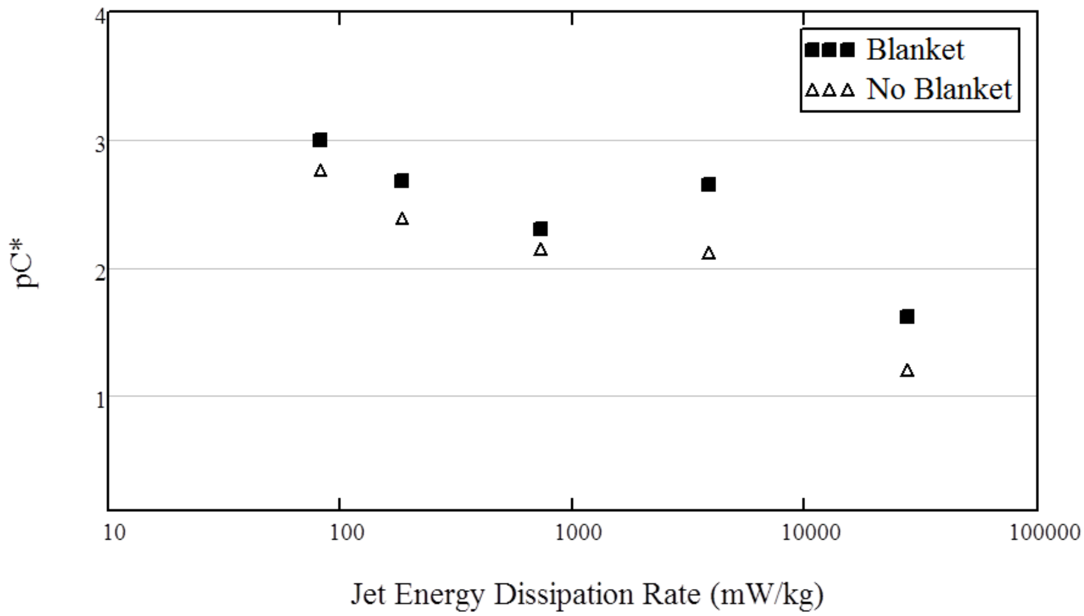

Figure 12. System performance with and without floc blanket at upflow velocity of 1.6 mm/s.

Discussion

The effluent suspended solids concentration remained unaffected by inlet jet EDR until about 300 mW/kg and decreased below acceptable performance at 6,000 mW/kg as interpolated from Figure 10. Based on this information, inlet jet EDR could be increased above that in current design guidelines without decreasing plant performance. Previous guidelines limit inlet velocity gradient (more correctly the EDR) to less than or equal to equivalent flocculator velocity gradient (Hudson, 1981). This research has shown that when a floc blanket and lamellar settlers follow the flocculator, overall performance begins to decrease when the sedimentation tank inlet has an EDR that is greater than 60 times the EDR of the flocculator in the 1.2 mm/s case and 63 times greater in the 1.6 mm/s case (Figure 9). Given that performance is still acceptable at higher jet EDR, smaller inlet jets with a higher velocity can be used to ensure the inlet jet is able to resuspend the floc density current and to decrease the required size of inlet manifolds.

Design guidelines suggest that flocs would have been broken to some degree in any EDR that exceeded the flocculator EDR. Given that deterioration in system performance was not observed until the inlet jet EDR was much higher than the flocculator (~60 times higher for 1.2 mm/s and ~63 times higher for 1.6 mm/s), the system can perform well with a higher inlet jet EDR. If flocs are indeed broken at an EDR that exceeds the flocculator EDR, then (1) the tube settler capture velocity was sufficient to capture the smaller flocs or (2) the floc fragments were captured in the floc blanket. Only at an EDR >300 mW/kg did the effluent turbidity begin to increase. A closer analysis of EDR gradient in the sedimentation tank influent jet would be needed to determine the actual size of the region where the maximum EDR is obtained.

Summaries

Based on the experimental results, inlet jets for floc blanket sedimentation systems could be designed at higher EDR and thus higher velocities to ensure floc density current resuspension without negatively impacting the effluent water quality. For the AguaClara design, a suggested EDR upper limit for the inlet jet is 300 mW/kg. For a 1 m wide sedimentation tank and an upflow velocity of 1 mm/s this corresponds to a velocity of 340 mm/s. At this velocity in a full-scale plant with rectangular diffusers (with the width of the diffuser being the design value to achieve the specified velocity), the minor head loss at the exit of the diffuser is 6 mm and should be taken into account in the hydraulic design. It is important to note that average velocity gradient is not an appropriate design parameter for the flow passages between the flocculator and sedimentation tank if the goal is to prevent excessive breakup of flocs because flocs are broken by the maximum EDR they experience and the EDR is a function of the flow geometry as well as the velocity. In comparison to recommended values for inlet velocities of 10 to 25 mm/s (AWWA/ASCE, 2012), the results of this research suggest up to 340 mm/s is permissible for a 1.5 mm thick plane jet before a change in performance is apparent in the system. It is apparent that general water treatment plant design guidelines do not apply to the AguaClara system or by inference to other upflow sedimentation reactors with floc blankets, and suggest that design parameters could be re-evaluated to optimize performance.

Only at extremely high inlet jet EDR did the experimental system produce an unacceptable water quality. At the lower end of EDR range tested, the jet was unable to resuspend the returning floc density current and led to sludge accumulation. In a full-scale system, biodegradation of accumulated sludge could result in gas production; and dissolved gas flotation of flocs to the top of the sedimentation tank. In order to resuspend the floc density current, a minimum jet velocity of 75 mm/s is suggested for the given system and lab conditions. The inability of a jet to resuspend the floc density current could be better characterized by determining the momentum of the two flows (floc density current and inlet jet). Further research to determine the minimum inlet jet requirements to suspend the floc density current should be based on momentum to accommodate the changing flocculated water momentum and floc density current concentrations. The results of this research indicate that AWWA and 10 State Standard design guidelines for upflow sedimentation tank inlets such as the AguaClara design is not useful.

Increasing inlet jet EDR reduces conduit size without significantly changing particle removal efficiency as demonstrated in this research. Since smaller conduits are less expensive, plant construction costs are less. There is ultimately a limit to the EDR that can be applied to a flocculated suspension before performance decreases in the system. However, there is a region before this limit where flocs appear to be broken into smaller aggregates that can still be captured by lamellar sedimentation where there is no decrease in performance. It is uncertain which mechanism (particle capture by the floc blanket or tube settlers) achieves the removal of broken flocs and further investigation into the removal of flocs and colloidal particles in a floc blanket system is needed. This information with additional research into the mechanistic interaction of the inlet jet flow with the floc density current could provide more definitive design guidelines based on a physical understanding of floc-shear interactions (rather than empirical) for both AguaClara and other sedimentation tanks.

Bibliography

AWWA/ASCE. (2012). Water Treatment Plant Design (5th ed.). American Water Works Association & American Society of Civil Engineers, McGraw-Hill.

Bache, D. H., & Gregory, R. (2010). Flocs and separation processes in drinking water treatment: a review. *Journal of Water Supply: Research and Technology—AQUA*, *59*(1), 16.

Baldyga, J., Bourne, J. R., & Gholap, R. V. (1995). The influence of viscosity on mixing in jet reactors. *Chemical Engineering Science*, *50*(12), 1877–1880.

Binnie, C., & Kimber, M. (2013). *Basic Water Treatment* (5th ed.). The Royal Society of Chemistry.

Chen, L, Lee, D., and Chou, S. (2006) Charge reversal effect on blanket in full-scale floc blanket clarifier. *Journal of Environmental Engineering*, *132*(11). 1523-1526.

Cleasby, J. L. (1984). Is Velocity Gradient a Valid Turbulent Flocculation Parameter? *Journal of Environmental Engineering*, *110*(5), 875–897.

Cornell University Water System. (2014). *Drinking Water Quality Report*. Ithaca, NY.

Edzwald, J. K. (2011). *Water Quality & Treatment: A Handbook on Drinking Water* (6th ed.). New York: McGraw-Hill. Retrieved from http://accessengineeringlibrary.com.proxy.library.cornell.edu/browse/water-quality-and-treatment-a-handbook-on-drinking-water-sixth-edition

Haarhoff, J., & Van Der Walt, J. J. (2001). Towards optimal design parameters for around-the-end hydraulic flocculators. *Journal of Water Supply: Research and Technology - AQUA*, *50*(3), 149–159.

Head, R., Hart, J., and Graham, N. (1997). Simulating the effect of blanket characteristics on the floc blanket clarification process. *Water Science Technology*. *36*(4) 77-84.

Hurst, M., Weber-Shirk, M., Charles, P., & Lion, L. W. (2014). Apparatus for observation and analysis of floc blanket formation and performance, *140* (1), 11–20. *Journal of Environmental Engineering*.

Logsdon, G. S. (2006). How Waterborne Disease Outbreaks Relate to Treatment Failures. *Association of Environmental Engineering & Science Professors*.

Recommended Standards for Water Works. (2012). Great Lakes - Upper Mississippi River Board of State and Provincial Public Health and Environmental Managers, Albany, NY.

Sung, S., Lin, W., Chen, L., and Lee, D. (2004). Spatial stability of floc blanket in full-scale floc blanket clarifiers. *Journal of Environmental Engineering* 130:1481-1487.

Tse, I. C., Swetland, K., Weber-Shirk, M. L., & Lion, L. W. (2011). Method for quantitative analysis of flocculation performance. *Water Research*, *45*(10), 3075–84. doi:10.1016/j.watres.2011.03.021

CHAPTER 3. REVISITING HYDRAULIC FLOCCULATOR DESIGN FOR USE IN WATER TREATMENT SYSTEMS WITH FLUIDIZED FLOC BEDS

Abstract[4]

In water treatment, flocculation creates aggregated particles or flocs large enough to be removed by downstream processes of sedimentation and filtration. Fluidized beds of flocs (floc blankets) are sometimes included in upflow sedimentation processes because they can significantly improve sedimentation tank particle removal when plate or tube settlers are used. The overall performance of a sedimentation tank containing a floc blanket is influenced by the characteristics of incoming flocs from the flocculator. Floc blankets provide an additional opportunity for aggregation of colloidal particles that enables a reduction in the size of the flocculators while improving particle removal efficiency. In this study, laminar flow flocculators varying in velocity gradient (G) and residence time (θ) were tested in a laboratory scale water treatment system with a floc blanket. Results indicate that increasing G (range of 74-251 s^{-1}) while decreasing residence time from 269 s to 80 s and maintaining a constant $G\theta$ (~20,000) improved particle removal. These results indicate that velocity gradients greater than existing design recommendations may be used to reduce flocculator residence times (and associated construction costs) when upflow sedimentation with a floc blanket and overlying lamellar plate or tube settlers are employed subsequent to flocculation. Further reduction of the residence time to 24

[4] The contents of this chapter have been published in *Environmental Engineering Science* with co-authors M.L. Weber-Shirk and L.W. Lion.

s with a G of 251 s^{-1} resulted in a settled water turbidity of 14 NTU. When varying θ at a constant G of 72s^{-1} an apparent minimum in settled effluent turbidity at 0.15 NTU was observed at the middle residence time tested (θ = 211 s) suggesting that long hydraulic flocculator residence times may be suboptimal.

Introduction

Designing an efficient water treatment process train that includes flocculator, floc blanket, plate settlers, and sand filtration is hindered by a limited understanding of how these sequential processes interact. Bache and Gregory (2010) have noted that smaller flocs are more desirable for floc blanket clarifiers and it follows that it might be beneficial to design upstream flocculators to produce smaller flocs. Small flocs can be produced by reducing flocculator hydraulic residence time (θ) so that flocs do not have time to grow very large, or through increasing fluid shear by increasing the velocity gradient (G) so that the size of flocs is limited. Flocs formed under conditions of higher shear are smaller and thus denser (Burban et al., 1989; Carissimi et al., 2007). However, excessively high shear produces very small flocs that may settle more slowly than the capture velocity of a sedimentation system resulting in unacceptable performance (Garland et al., 2016). Thus, it is unclear how varying flocculator residence time and velocity gradient might beneficially change the floc blanket suspended solids concentration and the system performance as measured by settled effluent (or residual) turbidity.

Flocculator design is traditionally based on the product of G and θ, known as the Camp number ($G\theta$). Although G may only be appropriate for laminar flow conditions (Cleasby, 1984), it is conventionally used for design of turbulent flocculators. The flocculators used in this study were laminar flow and thus G is an appropriate parameter for the laboratory scale flocculator. Suggested values for $G\theta$ for turbulent mechanically mixed flocculators range from 20,000-75,000 with G ranging from 20 to 75 s^{-1} (AWWA/ASCE, 2012). It was not assumed that these parameters were directly applicable to a laminar flow tube flocculator especially given the non-uniformity of the energy dissipation rate in mechanically mixed flocculators (Bouyer et al., 2005).

The recommended minimum residence time for flocculators varies from 20 minutes (AWWA/ASCE, 2012) to 30 minutes (*Recommended Standards for Water Works*, 2012). It is likely that guidelines for flocculator G and θ were developed based, in part, on experience where a low Peclet number mechanically mixed flocculator was followed by a conventional horizontal flow sedimentation tank. The applicability of these guidelines is uncertain in cases where a high Peclet number hydraulic flocculator (Weber-Shirk & Lion, 2010) is followed by an upflow sedimentation tank with a floc blanket and lamellar sedimentation.

Smaller flocculators use fewer materials and cover a smaller area reducing the overall cost of the plant. Given the conventional design criterion for $G\theta$, increasing G would mean a subsequent decrease in θ to maintain constant $G\theta$. In the laminar regime, G scales with the square root of the average energy dissipation rate, $\bar{\varepsilon}$. When using turbulent, hydraulic flocculators, increasing $\bar{\varepsilon}$ can be achieved by decreasing baffle spacing and θ can be decreased reducing the flocculator volume. It is not clear whether this trade-off is capable of producing flocs that will build a high performing floc blanket or that will be removed by downstream processes. Smaller flocs (due to low coagulant doses) have been shown to increase blanket suspended solids concentration (Bache, 2010), likely due to the inherent fractal nature of flocs that makes small flocs denser. Hurst et al. (2010) found that floc blanket suspended solids concentration dictated performance of the system with higher concentrations improving performance. Given that the mechanism for solids removal in the floc blanket has been attributed to flocculation and/or filtration, it is possible that the capacity of a flocculator could be reduced in a process train with a floc blanket because the floc blanket will provide an opportunity for further flocculation.

In this research, experiments were conducted to determine the impact of flocculator design on a lab-scale water treatment plant with a flocculator, a floc blanket, and tube settlers. Seven alternative flocculator designs were compared: three flocculators with the same $G\theta$ and different G and θ values; three flocculators with the same G but increasing θ; and one flocculator with a high G and low θ.

Experimental Protocol

The lab scale experimental apparatus was the same as described by Hurst et al. (2014) with the exception that a floc weir was used to limit floc blanket height and almost all influent fluid was removed from the reactor by passage through tube settlers. A schematic of the apparatus is provided in Figure 13. The height of the floc weir was 86 cm from the bottom of the jet reverser. Velocity of water through the jet reverser was 1.6 m/s. Angle of the bottom slope is 45^o and diameter of the round inlet jet tube was 4.6 mm. Aerated tap water (average pH 7.36, total alkalinity 131 mg/L as $CaCO_3$, total hardness 150 mg/L as $CaCO_3$, dissolved organic carbon 1.83 mg/L, Cornell University Water System, 2014) was mixed with an 8 gram/L stock kaolinite clay suspension (R.T. Vanderbilt Co., Inc. Norwalk, CT.) to form a 100 Nephelometric Turbidity Unit (NTU) synthetic raw feed water. To maintain a steady influent suspended solids concentration, an inline turbidity meter monitored the turbidity (HF Scientific Microtol Inline Turbidity Meter, Range: 0-1000 NTU) and Proportional Integral Derivative (PID) control implemented with Process Control and Data Acquisition (ProCoDA, 2015) software was used to meter the clay stock. Polyaluminum chloride (PACl) (PCH-180 Holland Co., Adams, MA) was mixed to create a stock 567 mg/L as Al and added to the influent stream using a peristaltic pump (Cole Parmer MasterFlex L/S, 1.6- 100 RPM Peristaltic Pump). The flow rate of the pump was adjusted to obtain a PACl dose of 1.25 mg/L as Al. Effluent turbidity was measured with an inline turbidity meter (HF Scientific Microtol Inline Turbidity Meter, Range: 0-1000 NTU) after the tube settlers and recorded every 5 seconds for the duration of each experiment. Floc blanket concentration measurements were made through digital image analysis of light absorbance as described by Hurst et al. (2014). Images were acquired at 60-second intervals with a Basler (Basler, Ahrensburg, Germany) color SCA640-70FC IEEE-1394B camera

(658 X490 pixels) using an 8 mm lens. Image field of view was 98.9 cm x 73.5 cm. Images for the floc blanket solids concentration region (see region indicated in Figure 13) were processed post experiment to obtain suspended solids concentrations using LabVIEW software.

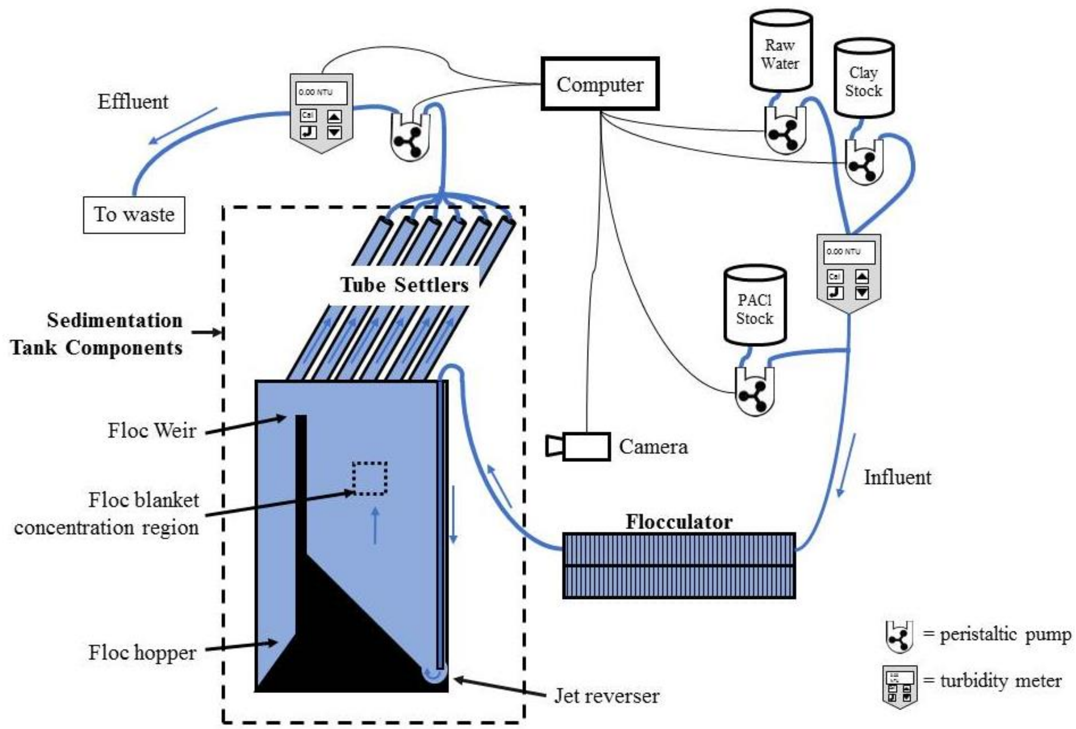

Figure 13. Design schematic of experimental apparatus. Influent to the sedimentation tank from the flocculator entered through a tube directed downward into the jet reverser. The flow was redirected upward by the semicircular jet reverser. The region of interest utilized for image analysis of floc blanket suspended solids concentrations is indicated with dashed lines. 10% of the total flow was sent to waste because it was insufficient to support an additional tube settler. Items in the shaded region indicate the post flocculator processes (i.e., the floc blanket plus tube settlers) considered in the sedimentation tank.

Performance of the system comprised of a flocculator, sedimentation tank, and tube settlers with no floc blanket was determined using the effluent turbidity after one full hydraulic residence time of the flocculator, sedimentation tank, and tube settlers.

The beginning of steady state for performance was defined as when the floc blanket height reached the top of the floc weir and the floc blanket concentration was constant within ± 2.5% of the mean concentration over the residence time of fluid in the floc blanket. After steady state was reached, data was averaged for one hydraulic residence time of the sedimentation tank (8.3 min) to obtain steady state floc blanket concentration and effluent turbidity.

In a typical water treatment process train a filter would follow sedimentation and, assuming 90% particle removal through filtration, the highest turbidity that could be sent to the filter and still produce a final effluent turbidity at or below EPA standards would be 3 NTU. Thus, settled effluent turbidity $\geq$3 NTU was adopted as criteria for failure of the upstream flocculator/floc blanket/tube settler system. The time required to form each floc blanket was also noted and $G\theta$ combinations that resulted in long formation times are considered undesirable.

Six tube settlers with a capture velocity (also referred to as a critical velocity) of 0.1 mm/s were utilized for this experiment. Tubes were 1in. PVC with a flow rate of 0.9 mL/s (per tube) set at 60^o from the horizontal. The flocculator energy dissipation rate was altered by changing the diameter of the flocculator tubing and the flocculator hydraulic residence time was adjusted by changing the length of tubing. Energy dissipated in the flocculator was determined by first calculating the major head loss due to laminar flow through the same length of straight tube using the Hagen–Poiseuille equation,

$$h_f = \frac{128\nu}{g\pi} \frac{LQ}{{D_{Tube}}^4} \tag{1}$$

where: ν is the kinematic viscosity of water (1.0 mm^2/s at 20°C), L is the length of the flocculator, Q is the flow rate, and D_{Tube} is the inner diameter of the tube.

Total energy losses accrued (including losses caused by the curvature of the helically coiled flocculator, h_{Coil}) were determined according to Berger et al. (1983)):

$$h_{Coil} = h_f \left\{ 1 + 0.033 \left[log\left(Re\sqrt{\frac{D_{Tube}}{D_{Coil}}} \right) \right]^4 \right\} \tag{2}$$

where: h_f is the major head loss from Equation 1, D_{Tube} is the inner diameter of the flocculator tube, D_{Coil} is the diameter of the coil and Re is the Reynold's number ($Re = \frac{VD_{Tube}}{\nu}$, where ρ is the density of water, V is the average velocity of the fluid) of the flow which ranged from 814 to 1222. The average energy dissipation rate (EDR), $\bar{\varepsilon}_{Flocculator}$, was determined by:

$$\bar{\varepsilon}_{Flocculator} = \frac{h_{Coil}g}{\theta} \tag{3}$$

Where: θ is the hydraulic residence time of the flocculator.

Average velocity gradient, G, was calculated by:

$$G = \sqrt{\frac{\bar{\varepsilon}_{Flocculator}}{\nu}} \tag{4}$$

Characteristics of the experimental flocculators are summarized in Table 2. Replicate experiments were performed for each $G\theta$ combination.

Table 2. Characteristics of each flocculator for each set of experiments.

	D_{Tube} (mm)	θ (s)	G (s^{-1})	$G\theta$	*Re*	*De*	Calculated Head loss (cm)	Mean Floc Blanket Formation Time (hr)*
1	6.5	80	251	20,080	1222	264	56.0	12.9
2	7.9	159	126	20,034	976	243	27.8	25.5
3	9.5	269	74	19,906	815	262	15.2	16.1
4	9.5	24	72	1,728	815	213	1.2	18.6
5	9.5	211	72	15,192	815	213	11.0	13.1
6	9.5	1425	72	102,600	815	213	74.0	12.1
7	6.5	24	251	6,024	1222	325	15.4	22.1
*Values are averages of two experiments.								

Major head loss was measured for flocculator 2 (G=126 s^{-1}, θ=159 s) to verify calculations. Theoretical head loss was calculated to be 27.8 cm using Equation 1 and 2 and actual head loss was measured with a pressure sensor to be 26.2 cm. Due to coagulant and clay to the walls, head loss increased with run time. Approximately 0.7% of influent was lost to flocculator walls and head loss increased at a mean rate of 10.4 mm/hr during experiments. Consequently, in all flocculators final G was higher than initial flocculator G.

Energy dissipation rate through the floc blanket is a function of the solids concentration within the floc blanket and was calculated as follows (Hurst et al., 2010):

$$\bar{\varepsilon}_{FB} = \frac{gV_{Up}}{\Phi}\frac{0.687C_S}{\rho_{Water}} \tag{5}$$

Where V_{Up} is the upflow velocity of the sedimentation tank, C_S is the suspended solids concentration of the floc blanket, Φ is the porosity of the floc blanket (85% based on settling tests) and ρ_{Water} is the density of water (998 kg/m^3 at 20^{o}C). A G for the floc blanket, G_{FB}, was determined by combining Equation 4 and Equation 5 and that the energy dissipation rate of the flocculator, $\varepsilon_{Flocculator}$, is substituted by the energy dissipation rate of the floc blanket, ε_{FB}:

$$G_{FB} = \sqrt{\frac{\bar{\varepsilon}_{FB}}{\nu}} \tag{6}$$

Results

An example of all data collected for an experiment is presented in Figure 14. A summary of steady state floc blanket concentration and effluent turbidities can be found in Table 3.

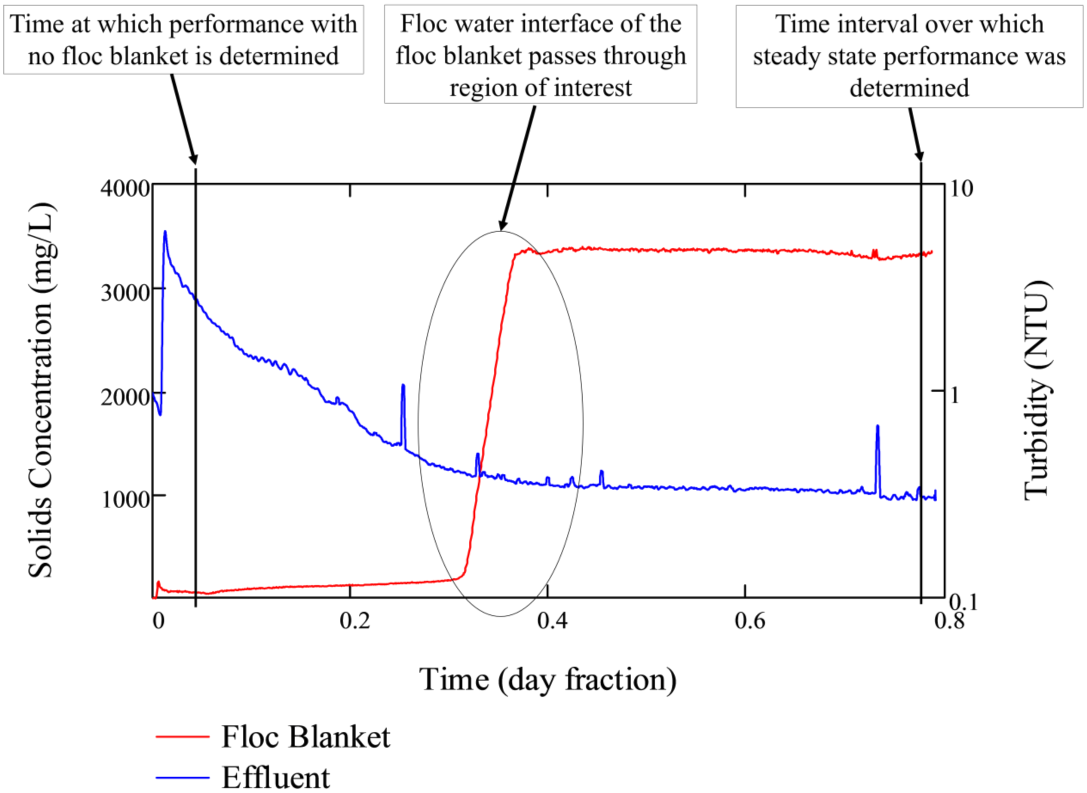

Figure 14. Example of floc blanket suspended solids concentration and effluent turbidity over time through an experiment (G=72s-1 θ=211 s). Effluent turbidity is plotted on the secondary y-axis. The total length of time used for averaging both steady state and no floc blanket performance is 150 seconds.

Table 3. Experiment results for each flocculator.

	θ (s)	G (s^{-1})	$G\theta$	Steady State Floc Blanket Concentration (mg/L)*	Steady State Effluent Turbidity (NTU)*
1	80	251	20,080	4,300	0.15
2	159	126	20,034	4,100	1.9
3	269	74	19,906	3,700	2.2
4	24	72	1,728	4,500	0.38
5	211	72	15,192	3,700	0.15
6	1425	72	102,600	2,100	0.8
7	24	251	6,024	5,500	14.1
*Values are averages of two experiments.					

Maintaining a constant $G\theta$ and varying G

The velocity gradient, G, of the flocculator was changed while maintaining a constant $G\theta$ of approximately 20,000. Flocculators with G values of 74, 126 and 251 s^{-1} (EDR of 5.5, 16 and 63 mW/kg, respectively) were utilized with a simulated raw water of 100 NTU and PACl dose of 1.25 mg/L as Al. Floc blanket suspended solids concentrations increased slightly with the higher flocculator G while tube settler turbidity decreased with a higher flocculator G (Figure 15). The effluent turbidity of the two flocculators with the lower G values was on the borderline of failure.

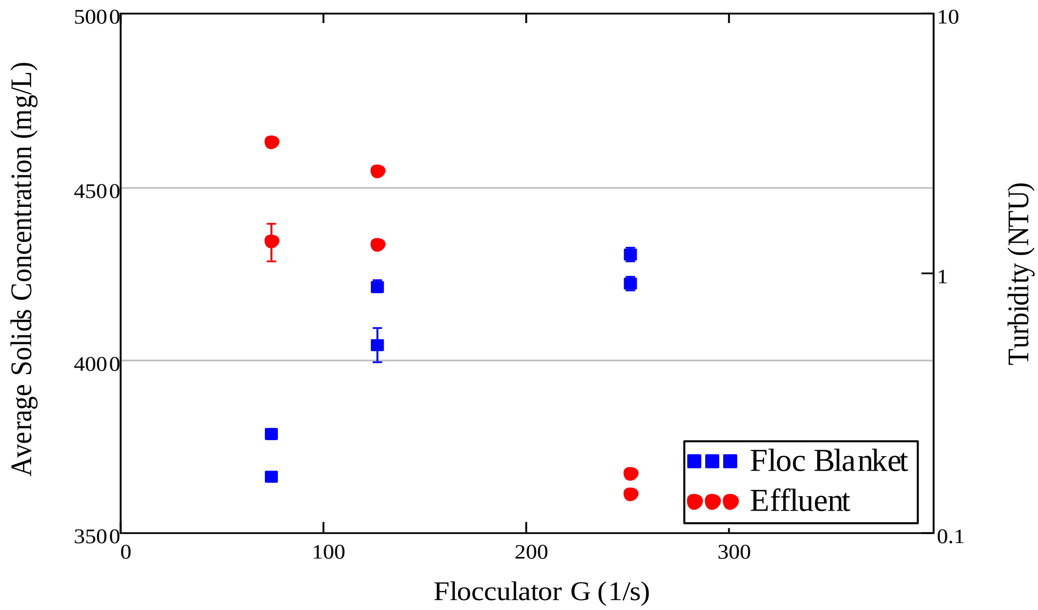

Figure 15. Steady state average suspended solids concentrations in the floc blanket and effluent turbidity at flocculator G values 74, 126 and 251 s^{-1} and constant $G\theta \approx 20{,}000$. Effluent turbidity points correspond to the secondary y-axis. Error bars indicate the standard deviation of each experiment however they are about the same size of the point symbol in many cases.

Effluent turbidity without a floc blanket was not significantly different across experiments (Figure 16). Based on the difference in performance with and without a floc blanket, the highest *G* experiment demonstrated the largest improvement and the best performance when the floc blanket was added. The lower and intermediate *G* experiments also improved with the presence of a floc blanket.

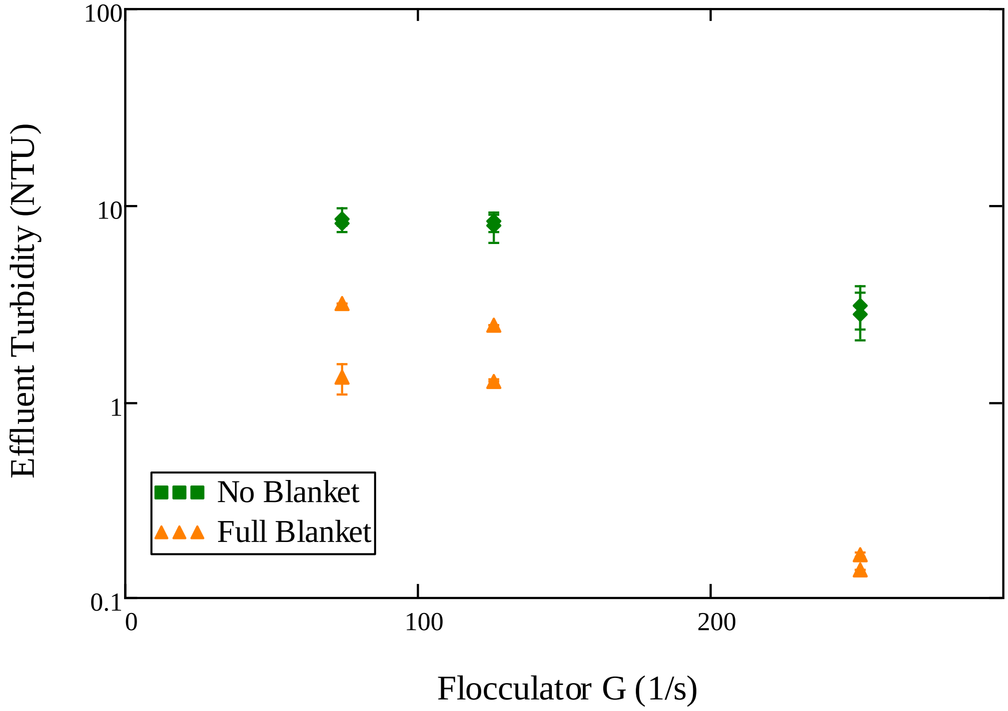

Figure 16. System performance with and without a floc blanket for experiments with increasing *G* and constant *Gθ*. Error bars are shown however they are about the same size of the point symbol in many cases.

Changing flocculator residence time

Experiments were conducted holding flocculator *G* constant (72 s^{-1} and close to the lowest *G* value tested at constant *Gθ*) and changing *θ* (24, 210 and 1425 seconds). As flocculator residence time increased, the floc blanket suspended solids concentration decreased (

Figure 17). Floc blanket suspended solids concentration for the longest residence time averaged 2,100 mg/L and increased to 4,500 mg/L for the shortest residence time. Effluent turbidity reached minimum values at the intermediate 211 s residence time.

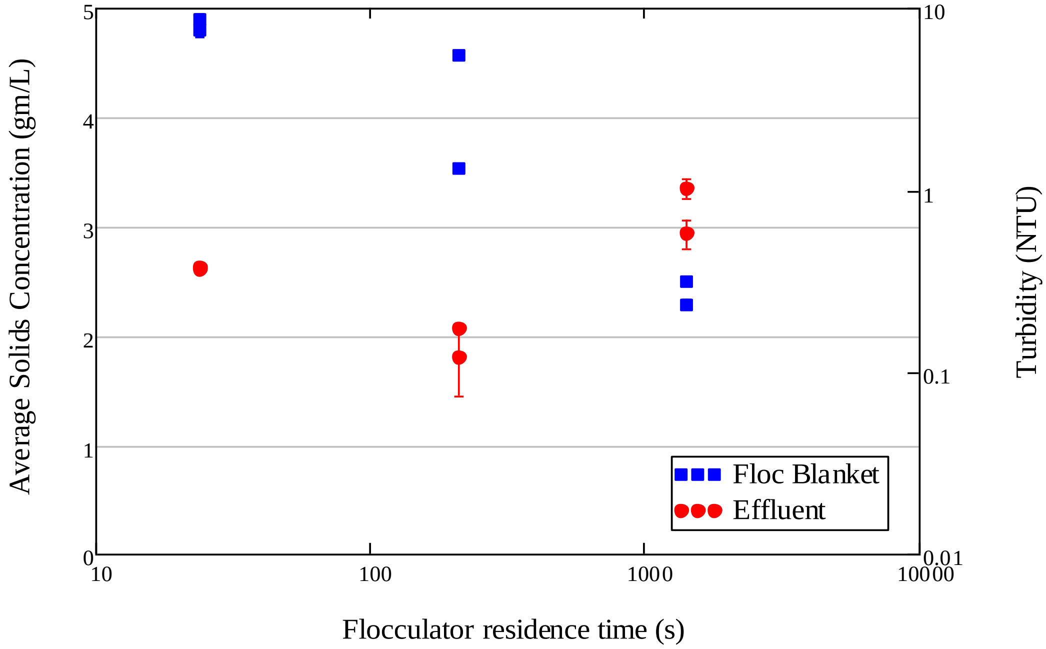

Figure 17. Steady state average system concentrations at $G = 72\ s^{-1}$ and varying flocculator residence time. Error bars are shown however they are about the same size of the point symbol in many cases.

Effluent turbidity without a floc blanket was highest for the lowest residence time flocculator and very similar at higher residence times (Figure 18). As the residence time of the flocculator increased, the contribution of the floc blanket to solids removal tended to decrease.

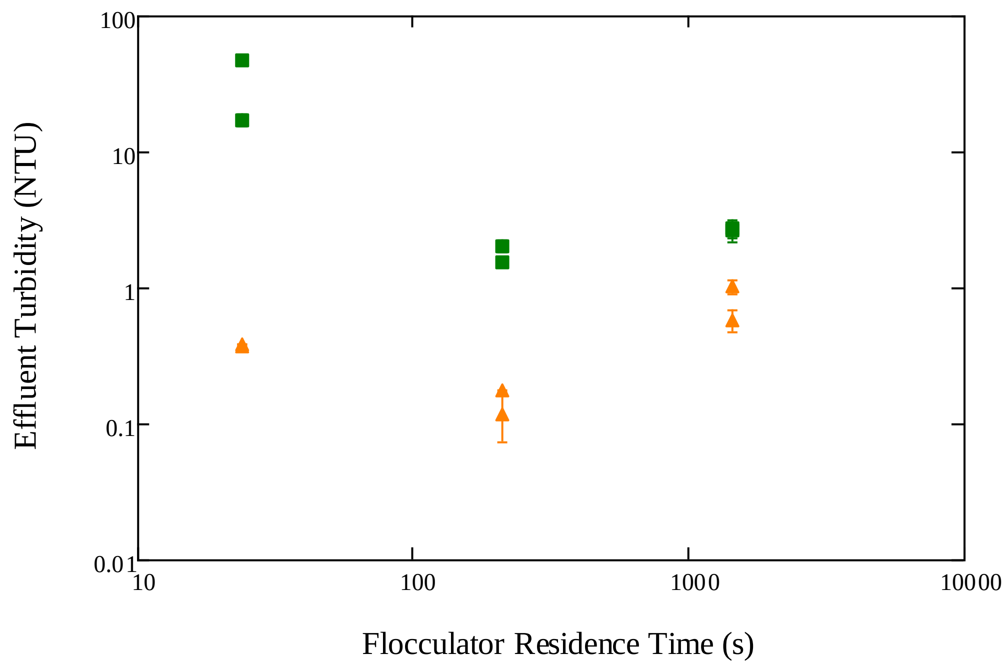

Figure 18. System concentrations with and without a floc blanket for experiments with increasing θ and constant G. Error bars are shown however they are about the same size of the point symbol in many cases.

Given that the lowest residence time flocculator (G = 72^{-s}) had a higher effluent turbidity than other experiments with similar G (

Figure 17) and that higher flocculator G values produced lower effluent turbidity (Figure 15), it was expected that increasing flocculator G while maintaining the residence time might improve system performance. Figure 19 shows the results of the high G (251 s^{-1}), low θ (24 s) experiment alongside the low G (72 s^{-1}), low θ experiment in Figure 18 that produced high effluent turbidity. Both floc blanket concentration and effluent turbidity increased with the higher G flocculator. Effluent turbidity averaged 14.3 NTU for both experiments indicating the system was in failure with this flocculator.

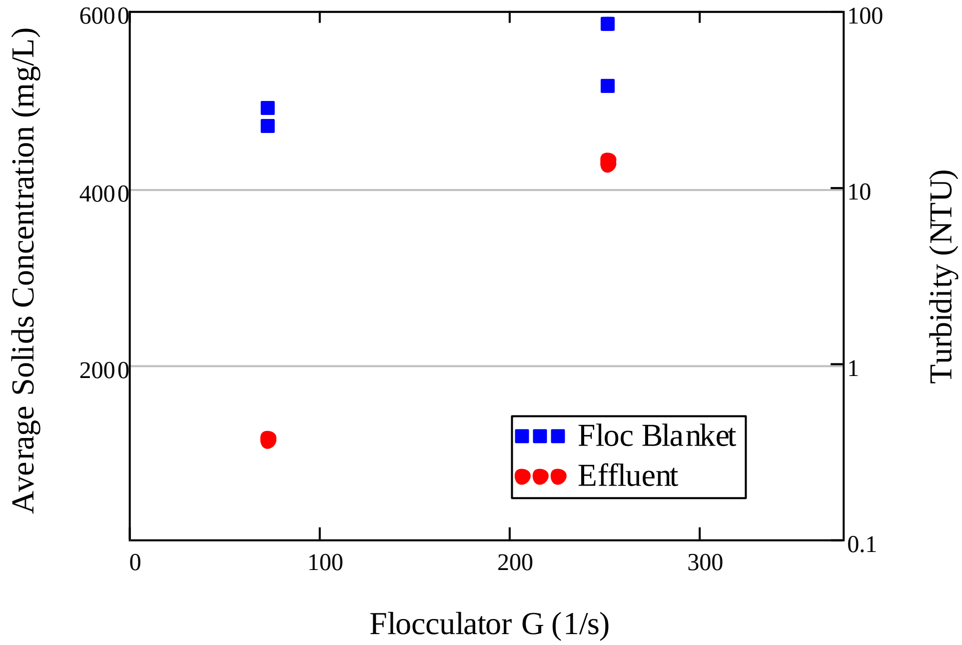

Figure 19. Steady state average system concentrations at low and high *G* and constant flocculator residence time. Error bars are shown however they are about the same size of the point symbol in many cases.

Discussion

Flocculators and floc blanket concentrations

Increasing the velocity gradient of the flocculator would be expected to produce smaller flocs as floc size scales inversely with shear (Parker et al., 1972; Spicer and Pratsinis, 1996; Jarvis et at., 2005). Generally, small flocs produce higher floc blanket concentrations (Hurst et al., 2010; Su et al., 2004; Bache, 2010). Higher floc blanket suspended solids concentrations were observed with higher *G* flocculators and low residence time flocculators supporting expectations that smaller flocs were produced from these conditions. In the case of the short residence time flocculator, floc size was likely set by insufficient opportunity for particle collisions.

A floc resulting from a collision between a small and large floc (particle to cluster aggregation) will have a higher mass fractal dimension with a higher density than the original large floc (Gregory, 1997). Additionally, flocs formed in high *G* conditions were observed by Jung et al. (1996) to be more compact and had a higher fractal dimension. We hypothesize that the collisions between small flocs coming from the flocculator and large fully grown flocs in the floc blanket produce flocs with a higher mass fractal dimension increasing the floc density and thus the solids concentration. As flocs enter the floc blanket where shear is much lower than that in the flocculator (G_{FB} = 4.4-6.4 $s^{-1}$for floc blankets produced in these experiments calculated by Equation 6; flocculator *G*s of 72-251 s^{-1}), they will grow in size until the shear in the floc blanket prevents further growth. As small flocs enter the floc blanket from the flocculator, they collide with large floc blanket flocs resulting in a floc with increased density and fractal dimension. As a result, flocculators that produce a large number of small flocs (high *G* or low residence time flocculators) are expected produce higher concentration floc blankets.

Li and Logan (1997) looked at collision efficiencies between fractal aggregates and colloids and concluded that colloid removal efficiencies were related to the porosity of the fractal. Larger, more porous flocs were seen to be more permeable allowing water to flow through them achieving rectilinear fluid motion and capture of small colloids. As the large, porous flocs accumulated colloids and floc porosity decreased, water would tend to travel around the fractal aggregate (curvilinear motion) and decrease colloid capture. This observation also suggests that floc blanket flocs may have a limited capacity for collisions with small particles and finite capacity for particle to cluster aggregation. In the case of the floc blanket, dense flocs resulting from particle to cluster aggregation would remain fluidized and increase the suspended solids concentration as well as coupled energy dissipation rate (and thus number of collisions of small like-sized particles) in the floc blanket. Thus, small particle removal may occur through a combination of particle to cluster aggregation (creating dense flocs and a higher floc blanket suspended solids concentration) and increased like-sized small floc collisions promoted by the ensuing higher energy dissipation rate in the floc blanket. Tambo and Hozumi (1979) modeled contact flocculation under the assumption that only collisions between grown flocs and small flocs were significant. The basis for this assumption was directed at modeling the number of small flocs removed in the fluidized bed however the assumption is as relevant to understanding the increase in floc blanket suspended solids concentration as it is to what collisions are significant.

The longest residence time, lowest *G* flocculator created the least concentrated floc blanket (

Figure 17). Flocs from this flocculator would have been the largest due to the low *G* and the number of small flocs would have been minimized due to the long residence time. As a result it is expected that there would have been very few small flocs to collide with floc blanket flocs to increase the overall suspended solids concentration. This reasoning is consistent with the low floc blanket solids concentrations observed in the low G long θ experiment.

Potential for collisions in the floc blanket

The mechanism by which the floc blanket improves system performance in terms of settled water turbidity is thought to be removal of small flocs through flocculation (collisions between small flocs) and/or filtration (collisions between small and grown flocs). Higher floc blanket suspended solids concentrations would be expected to have better removal because the distance a floc must travel before colliding with another floc is small compared to a lower concentration floc blanket. Higher shear in the floc blanket at high suspended solids concentration would also increase the number of small floc collisions occurring in the floc blanket. The overall performance of a floc blanket is controlled by the removal of small flocs that would otherwise escape the tube settlers. Growing flocs to the largest possible size is not the operational goal; instead it is to ensure the smallest flocs grow to be large enough to be captured by the tube settlers. Thus, floc blanket design should encourage collisions with the smallest flocs to reduce effluent turbidity. This can be achieved with higher floc blanket suspended solids concentrations that create higher shear and hence more collisions between small flocs and between small and grown floc blanket flocs.

In experiments where G was varied but $G\theta$ remained the same (Figure 15 and Figure 16), the two highest G flocculators produced blankets with very similar suspended solids concentrations but notably different effluent turbidities (0.15 NTU at G = 251 s^{-1} and 1.9 NTU at G = 126 s^{-1}). Given the high suspended solids concentration of the floc blanket and smaller size of flocs exiting from the highest G flocculator, it is possible that this $G\theta$ combination represents an optimal condition where the floc blanket suspended solids concentration is high, increasing collisions, and the flocs from the flocculator are small so that the smallest flocs, that would have otherwise escaped the tube settlers, grow to a size that can be captured. When the same flocculator G with lower residence time was used, effluent turbidity was very high (14.3 NTU) even though the floc blanket suspended solids concentration was high (Figure 19). Poor performance in this case was likely the result of too many small flocs with sedimentation velocities less than the capture velocity of the tube settlers. Although some of these flocs were undoubtedly captured in the floc blanket, too many of them escaped and were not able to be captured by the tube settlers.

The lowest suspended solids concentration floc blanket was created by the low G, long θ flocculator (

Figure 17). Interestingly, the effluent turbidity of the system without a floc blanket in this case (Figure 18) was very similar to those for the intermediate θ flocculators suggesting that flocs leaving both flocculators were similar in overall size and had settling velocities higher than the capture velocity of the tube settlers. In Figure 18 it is apparent that there was a minimum steady state effluent turbidity at the intermediate residence time. Although the research presented here does not reveal the optimal residence time producing the lowest effluent turbidity, it is important to note that additional θ was not helpful, but in fact reduced system performance with a floc blanket.

Practical considerations

In practice, it takes time for a floc blanket to form and the high effluent turbidity during this interval is an important consideration. From experiments with constant $G\theta$, the low and high G flocculators had lower formation times relative to the intermediate G flocculator (Table 2) but all produced higher effluent turbidity without a floc blanket (Figure 16). From the experiments with varying flocculator θ, the intermediate and longest θ had reasonable effluent turbidity without a floc blanket (Figure 18) and formation times relative to the flocculator with the lowest θ (Table 2). For all cases tested, the formation time was generally longer in flocculators that produced poor effluent turbidity without a blanket during startup or during steady state operation. System performance would decrease in all cases if the tube settler capture velocity was increased and must be accounted for in system designs.

The results presented in this paper indicate that flocculator design can influence floc blanket suspended solids concentration and effluent turbidity and that some decrease in flocculator hydraulic residence time (and coupled construction costs) may be accomplished through the use of higher G flocculators. However, direct use of $G\theta$ based on the results presented above where the experimental flow was laminar should not be applied for system design for turbulent flocculators or flocculators with high temporal and spatial variability in energy dissipation rate. Hydraulic flocculation research under conditions of turbulence is needed to better define the tradeoff between hydraulic residence time and the energy dissipation rate.

Summaries

The research presented in this paper shows that the current guidelines do not produce optimal results when a floc blanket is used. At constant $G\theta$, the lowest velocity gradient tested (and the highest suggested by design guidelines) performed the worst (Figure 15) and the lowest settled effluent turbidity was observed at the highest velocity gradient tested. In experiments with constant G and varying θ, there was an apparent minimum in effluent turbidity (

Figure 17) where an increase in θ did not improve turbidity removal. Over the 62-fold reduction in experimental flocculator residence time tested (from 1425 s to 24 s), the effluent turbidity increased by about 0.43 NTU suggesting that smaller flocculator could be used in series with a floc blanket.

Flocculators used in this paper created a range of floc blanket concentrations (2,100 – 5,500 mg/L) when a constant PACl dose was used. Previous research has strongly suggested that higher floc blanket concentrations are related to better floc blanket performance (Gregory et al., 1996; Hurst et al., 2010) thus it might be possible to improve performance of a water treatment plant by designing a flocculator that will produce a high concentration floc blanket.

The experimental results suggest that, within reasonable limits, hydraulic flocculators with residence times that are shorter than recommended limits and velocity gradients above recommended limits might be a means to improve performance assuming a floc blanket and lamellar sedimentation are employed. Design of a water treatment plant has never been optimized for cost and/or performance and these results suggest imply that flocculators could be smaller, and likely less expensive, in optimized designs. Smaller flocculators use fewer materials and require less area to build. These results may be more directly applicable to hydraulic flocculators designed to have a more uniform energy dissipation rate as opposed to mechanical flocculators with a large difference between maximum and average energy dissipation rate. Further research is needed to understand how flocculator design, suspension properties, and coagulant dose control floc size distributions and subsequent particle capture by floc blankets and lamellar sedimentation.

Bibliography

AWWA/ASCE. (2012). Water Treatment Plant Design (5th ed.). American Water Works Association & American Society of Civil Engineers, McGraw-Hill.

Bache, D.H. (2010). Model of dynamic and macroscopic features of a floc blanket. *Journal of Water Supply: Research and Technology—AQUA*. 59(1), p.53.

Bache, D. H., and Gregory, R. (2010). Flocs and separation processes in drinking water treatment: a review. *Journal of Water Supply: Research and Technology—AQUA*, 59(1), 16. doi:10.2166/aqua.2010.028

Berger, S.A., Talbot, L. and Yao, L.-S. (1983). Flow in curved pipes. *Ann. Rev. Fluid Mech*. 15, pp.461–512.

Bouyer, D., Escudié, R. and Liné, A. (2005). Experimental analysis of hydrodynamics in a jar-test. *Process Safety and Environmental Protection*. 83(1), pp.22–30.

Burban, P.-Y., Lick, W. and Lick, J. (1989). The flocculation of fine-grained sediments in estuarine waters. *Journal of Geophysical Research*. 94(89), p.8323.

Carissimi, E., Miller, J.D. and Rubio, J. (2007). Characterization of the high kinetic energy dissipation of the Flocs Generator Reactor (FGR). *International Journal of Mineral Processing*. 85(1-3), pp.41–49.

Cleasby, J.L. (1984). Is velocity gradient a valid turbulent flocculation parameter? *Journal of Environmental Engineering*. 110(5), pp.875–897.

Cornell University Water System. (2014). *Drinking Water Quality Report*. Ithaca, NY.

Garland, C., Weber-Shirk, M. and Lion, L.W. (2016). Influence of variable inlet jet velocity on failure modes of a floc blanket in a water treatment process train. *Environmental Engineering Science.* 33(2), pp.79–87.

Gregory, R., Head, R. J. M., & Graham, N. J. D. (1996). The relevance of blanket solids concentration in understanding the performance of floc blanket clarifiers in water treatment. In H. H. Hahn, E. Hoffman, & H. Odegaard (Eds.), *Chemical Water and Wastewater Treatment IV* (pp. 17–29). Berlin: Springer. Retrieved from http://dx.doi.org/10.1007/978-3-642-61196-4_2

Gregory, J. (1997). The density of particle aggregates. *Water Science and Technology*. 36(4), pp.1–13.

Hurst, M., Weber-Shirk, M. and Lion, L.W. (2010). Parameters affecting steady-state floc blanket performance. *Journal of Water Supply: Research and Technology—AQUA*. 59(5), p.312.

Hurst, M., Weber-Shirk, M. and Lion, L.W. (2014). Apparatus for observation and analysis of floc blanket formation and performance. *Journal of Environmental Engineering*. 140, pp.11–20.

Jarvis, P., Jefferson, B., Gregory, J., and Parsons, S. A. (2005). A review of floc strength and breakage. *Water Research*. 39(14), pp.3121–37.

Jung, S.J., Amal, R. and Raper, J. A. (1996). Monitoring effects of shearing on floc structure using small-angle light scattering. *Powder Technology*. 88(1), pp.51–54.

Li, X.Y. and Logan, B.E. (1997). Collision frequencies between fractal aggregates acid small particles in a turbulently sheared fluid. *Environmental Science & Technology*. 31(4), pp.1237–1242.

Parker, D., Kaufman, W. and Jenkins, D. (1972). Floc breakup in turbulent flocculation processes. *J. Sanit. Eng. Div:Proc. Am. Soc. Civ. Eng*. SA1. pp.79–99.

Process Control and Data Acquisition (ProCoDA). (2015). https://confluence.cornell.edu/display/AGUACLARA/ProCoDA.

Recommended Standards for Water Works. (2012). Great Lakes - Upper Mississippi River Board of State and Provincial Public Health and Environmental Managers, Albany, NY.

Spicer, P.T. and Pratsinis, S.E. (1996). Shear-induced flocculation: the evolution of floc structure and the shape of the size distribution at steady state. *Water Research*. 30(5), pp.1049–1056.

Su, S.T., Wu, R.M. and Lee, D.J. (2004). Blanket dynamics in upflow suspended bed. *Water Research*. 38(1), pp.89–96.

Tambo, N. and Hozumi, H. (1979). Physical aspect of flocculation process--II. Contact flocculation. *Water Research*. 13, pp.441–448.

Weber-Shirk, M. and Lion, L.W. (2010). Flocculation model and collision potential for reactors with flows characterized by high Peclet numbers. *Water Research*. 44(18), pp.5180–5187.

CHAPTER 4. CHARACTERIZING PARTICLE REMOVAL IN WATER TREATMENT BY A PROCESS SEQUENCE OF HYDRAULIC FLOCCULATION, FLOC BLANKET, AND LAMELLAR SEDIMENTATION

***Abstract*[5]**

Sedimentation tanks can be designed to support floc blankets that provide improved removal of small particles and hydraulic self-cleaning with no accumulation of settled sludge. Floc blanket particle aggregation processes are not well understood as evidenced by the dearth of predictive equations characterizing performance. A mechanistic understanding of floc blanket particle aggregation mechanisms would facilitate optimization of the combined water treatment processes of hydraulic flocculation, floc blankets, and lamellar sedimentation. Four flocculators and three coagulant dosages were tested in an experimental water treatment plant system (hydraulic flocculation, floc blanket, and tube settlers) to establish performance values. Three categories of flocs in the floc blanket (residual, transitional, and hindered) were defined based on floc size and time-scale in the floc blanket. Three hypotheses explaining the aggregation of non-settleable (residual) particles by floc blankets were evaluated. Residual particles in floc blankets are either aggregating by collisions 1) with other residual particles, 2) with small flocs (transitional) that are concentrated in the floc blanket by capture and return to the floc blanket by lamellar sedimentation, or 3) with large flocs (hindered) that are retained by the floc blanket.

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[5] The contents of this chapter have been submitted to *Environmental Engineering Science* with co-authors M.L. Weber-Shirk and L.W. Lion.

Introduction

Sedimentation tanks with floc blankets, lamellar sedimentation, and sludge consolidation can be designed with a total depth less than 2 m and with a residence time of less than 30 minutes. These processes can treat high turbidity waters (of at least 1000 NTU) and reliably produce settled water that is less than 1 NTU (http://aguaclara.github.io). Floc blankets reduce settled water turbidity at no additional operating cost. These advantages suggest that floc blankets have the potential to play a significant role in both upgrades and expansion of sustainable water infrastructure. A mechanistic understanding of the role of floc blankets in reducing settled water turbidity could lead to improved water treatment plant designs with higher performance at a lower capital cost.

Floc blankets can improve water treatment plant performance through three distinct mechanisms. First, anaerobic degradation of accumulated settled sludge in conventional sedimentation tanks produces gas bubbles that carry flocs to the surface. Anaerobic degradation increases with temperature and will be exacerbated as water temperatures rise. Sedimentation tanks with floc blankets can be designed with sloped bottom geometry, a jet reverser, and a weir at the floc water interface (Garland et al., 2016) to completely eliminate settled sludge and thus prevent anaerobic conditions. Second, floc blankets can be designed to hydraulically transport suspended solids to a consolidation tank and then to be discharged without using mechanized sludge removal equipment in the sedimentation tank. Third, floc blankets significantly reduce the settled water turbidity.

Prior research on a process train consisting of hydraulic flocculation followed by floc blankets and lamellar sedimentation report that lamellar sedimentation significantly reduces effluent turbidity (Garland et al., 2016; Garland et al., 2017; Gregory, 1979; Hurst et al., 2014a; and Hurst et al., 2014b). Floc blanket performance is presumed to be influenced by the particle size distribution entering from the flocculator (Bache, 2010; Bache and Gregory, 2010; Garland et al., 2017; and Tambo & Hozumi, 1979). Given the multiple interactions between the processes of hydraulic flocculation, floc blankets and laminar sedimentation, it is difficult to draw conclusions from prior floc blanket investigations that did not include flocculation and lamellar sedimentation as integral components of the experimental process.

The addition of floc blankets in particle/fluid separation systems has been shown to produce lower effluent turbidity, improve sludge characteristics, operate at higher loading rates, and effectively treat higher turbidity flows (AWWA/ASCE, 2012). The mechanism for settled water turbidity (or residual turbidity) reduction by a floc blanket has yet to be elucidated. Several researchers have suggested that a floc blanket demonstrates flocculator and/or filter-like behavior in terms of the mechanisms that govern removal of small particles (Gregory, 1979; Tambo & Hozumi, 1979). Clear definitions of the proposed mechanisms and experiments to distinguish between the removal process are needed.

Floc blanket particle sizes range from primary colloidal particles to large flocs that have sufficiently high settling velocities to be retained by the floc blanket. Three classes of flocs are proposed here where each class has a specific time scale and size range: 1) residual particles, 2) transitional flocs, and 3) hindered flocs. Particles and flocs enter the floc blanket from the flocculator as residual and transitional. Residual particles can escape lamellar sedimentation and the treatment objective is to minimize this particle flux. The only other exit of particles from the floc blanket is over the floc hopper weir and that flux consists primarily of flocs that have a settling velocity that exceeds the upflow velocity of the sedimentation tank. Within the floc blanket, residual and transitional particles grow and are converted to hindered flocs. Figure 20 illustrates the proposed floc categories and indicates potential pathways and transformations.

> *Residual particles* are particles and flocs that do not have a settling velocity large enough to be captured by lamellar sedimentation (tube settlers in this research). These flocs are the smallest of the 3 categories and are either colloidal particles that have yet to make a successful collision or small flocs composed of a few particles (depending on the particle size and lamellar sedimentation capture velocity). The capture velocity of lamellar sedimentation is approximately a tenth of the sedimentation upflow velocity and thus these particles settle very slowly compared with the upflow velocity. As a result, residual particles are transported upward with the fluid through the floc blanket. Residual particles that are not converted to transitional flocs by the floc blanket will pass through the lamellar settlers and escape as residual

turbidity. The maximum diameter of residual flocs was predicted using the following equation from Adachi and Tanaka (1997).

$$V_t = \frac{g d_{Clay}^2}{18\Omega_{Floc}\nu_{H2O}} \frac{\rho_{Clay} - \rho_{H2O}}{\rho_{H2O}} \left(\frac{d_{Floc}}{d_{Clay}}\right)^{D_{Fractal}-1} \tag{1}$$

Where g is gravitational constant, d_{Clay} is the diameter of an experimental primary clay particle (7 μm determined by Sun et al., 2015), Ω_{Floc} is the shape factor for drag of flocs (1.875 from Tambo and Watanabe, 1978),ν_{H2O} is the kinematic viscosity, ρ_{Clay} is 2650 kg/m^3(Tambo and Watanabe, 1979), ρ_{H2O} is the density of water 998 kg/m^3 at 20^{o}C, d_{Floc} is the diameter of the floc to be solved for, and V_t is set equal to the lamellar sedimentation capture velocity. Weber-Shirk & Lion (2015) determined $D_{Fractal}$ = 2.3.

Transitional flocs have a settling velocity less than the upflow velocity of the floc blanket but larger than the capture velocity of the lamellar settlers and have not reached hindered size. Flocs can be added to this category by entering the floc blanket from the flocculator, by residual particles making successful collisions through the floc blanket and growing into the category, or by captured flocs from lamellar sedimentation returning to the floc blanket. Flocs leave the transitional category by falling over the floc weir or by making enough successful collisions to become hindered flocs. The transitional floc concentration is hypothesized to increase until the rate of removal (aggregation into hindered flocs plus removal over the floc weir) matches the rate that transitional flocs are entering the floc blanket (by transport from the flocculator, aggregation of residual particles creating transitional flocs, and by being returned to the floc blanket by lamellar sedimentation).

Hindered flocs have grown large enough to be retained by the floc blanket and thus they have a settling velocity equal to or exceeding the upflow velocity. Therefore, the minimum size floc in this category is the diameter that corresponds to the upflow velocity, d_{Upflow}, from equation 1. The terminal size ($d_{Terminal}$) hindered flocs can reach is hypothesized to be limited by the velocity gradient of the floc blanket and the strength of the flocs. Given the large number of flocs in the floc blanket, terminal floc size is likely weakly dependent on collisions. The authors predict that the hindered floc residence time is on the order of the formation time of the floc blanket because any floc that enters and is captured by the sedimentation tank will remain in the floc blanket until, at minimum, the floc blanket height increases to the height of the floc weir. Hindered flocs are wasted over the floc weir. Flocs of this size are abundant in the floc blanket and it would take a relatively small number of collisions for the smallest floc in this category (a floc diameter of 150 μm would settle at the upflow velocity based on equation 1) to reach terminal size (floc diameter of ~800 μm based on observations).

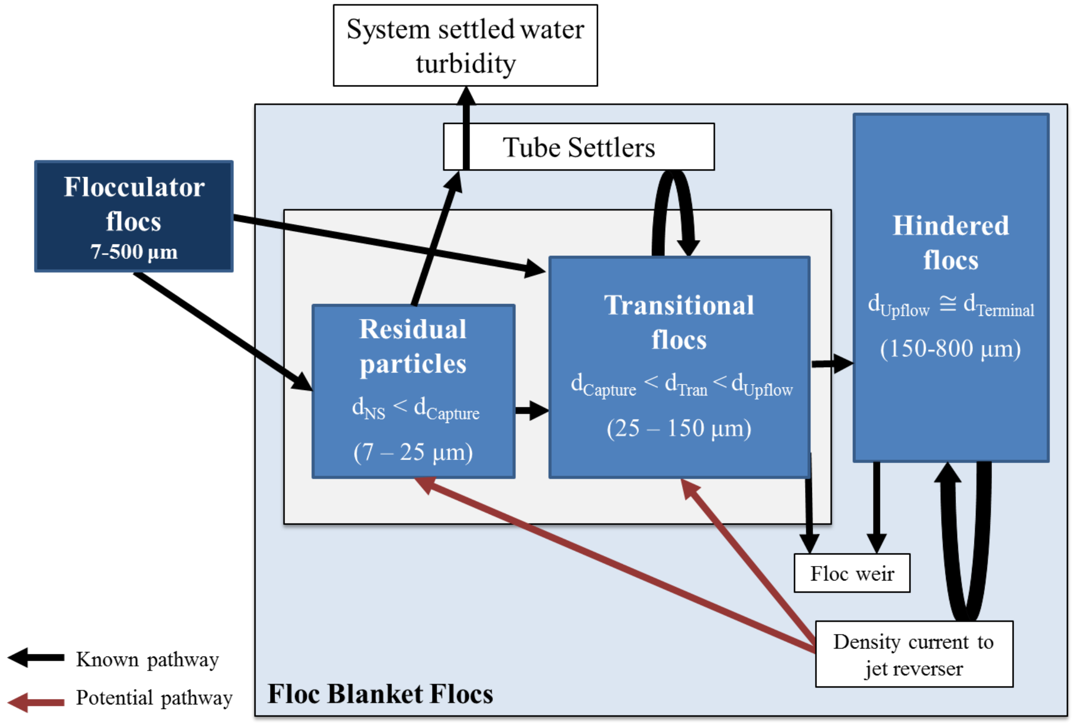

Figure 20. Diagram of floc categories in the floc blanket with pathways indicating the sources of each category. Floc sizes for these categories are estimated based on observations and capture velocities of the sedimentation tank and lamellar sedimentation.

There are 3 hypothesized particle interactions in the floc blanket that could result in reduced residual turbidity: 1) residual (non-settleable) particles aggregate with other residual particles, 2) residual particles aggregate with transitional flocs (Bache, 2010), and 3) residual particles aggregate with hindered flocs (Gregory, 1979; Tambo & Hozumi, 1979).

Collisions between residual particles (hypothesis 1) could be hydrodynamically favored in flocculation over collisions between residual particles and larger flocs because relatively large flocs have boundary conditions that decrease the possibility that smaller residual particles will make a collision (Adler, 1981; Han

& Lawler, 1992; Veerapaneni & Weisner, 1996; Xiao et al., 2013). This would suggest that hypothesis 1 is the most plausible mechanism. Two confounding factors are that transitional flocs and hindered flocs have higher number concentrations in the floc blanket and floc permeability could enable collisions between residual particles and larger flocs. Thus, transitional or hindered flocs may play a significant role in aggregation with residual turbidity.

The research presented in this paper examines the performance, as measured by settled water turbidity, of a water treatment system (hydraulic flocculator, floc blanket, tube settlers) created by different flocculators with approximately the same Camp number ($G\theta$) at 3 coagulant doses. Transient and steady state performances of the water treatment system are compared to expected performance based on two particle aggregation models.

Methods

The water treatment system comprised of a flocculator, sedimentation tank/floc blanket, and tube settlers is described in detail by Hurst et al. (2014a) with modifications described by Garland et al. (2017). A schematic of the system is presented in Figure 21. A total of four laminar flow flocculators with nearly constant Camp number ($G\theta$ ~20,000; values are approximate due to the availability of manufactured tube sizes) were examined for settled water turbidity, floc size distribution, and water treatment system performance. The particular Camp number was chosen because 20,000 was the lowest recommended for water treatment design

(AWWA/ASCE, 2012). In each case an inlet jet to the floc blanket (Garland et al., 2017) was used with a velocity gradient comparable to that employed in the flocculator. Each flocculator was made by helically coiling PVC tubing around either 8 or 13 cm diameter cylinders. Flocculator *G* values were adjusted by using tubing with different diameters and changing the diameter on which the tube was coiled. Hydraulic residence was set by the length of the tubing (see Garland et al., 2016 for further description on calculating flocculator parameters). Table 4 shows the parameters for each flocculator. In subsequent graphs presented, the legends use flocculator G to distinguish between flocculators tested.

For all experiments, Cornell tap water (average pH 7.67, total alkalinity 140 mg/L as $CaCO_3$, total hardness 150 mg/L as $CaCO_3$, dissolved organic carbon 1.80 mg/L Cornell University Water System, 2016) was passed through activated carbon, aerated, and temperature controlled before being used for experiments. A Masterflex peristaltic pump controlled the system flow rate for all experiments at 6 mL/s. Raw water was created by pumping a constantly mixed kaolin clay suspension (Vanderbilt Minerals, Norwalk, CT) at a stock concentration of approximately 8 g/L into the conditioned water line prior to a MicroTOL Inline Turbidity Meter. Raw water turbidity was kept constant at 100 Nephelometric Turbidity Units (NTU) by using proportional, integral, derivative (PID) control to adjust the speed of the pump delivering clay stock into the conditioned water line and using the raw water turbidity meter as feedback. Polyaluminum chloride (PACl) at 69.8 g/L as Al (Holland Company, Adams, MA) was diluted to 266 mg/L and pumped into the raw water with a peristaltic pump. Dosages were adjusted by changing the pump speed. All pumps were controlled and turbidity meter values read by ProCoDA software (ProCoDA, 2015).

Table 4 Experiments with flocculators and water treatment system performance.

Flocculator	Tube diameter (mm)	G (s^{-1})	θ (s)	Camp number ($G\theta$)	Reynolds Number*	Dean Number	Calculated Headloss (cm)	Inlet Jet G (s^{-1})
1	9.5	72	269	19,400	810	213	14	62
2	8	126	159	20,000	980	234	25	89
3	6.4	251	102	25,600	1,220	264	65	175
4	5.7	340	59	19,700	1,360	250	69	175
*Reynolds number is of straight pipe (VD/ν, where V is velocity through the tube, D is the diameter, and ν is dynamic viscosity). It is used to calculate the Dean number								

Sedimentation tank upflow velocity was 1.2 mm/s (set by the flow rate of the system pump) and tube settler capture velocity was 0.1 mm/s (set by a dedicated peristaltic pump). All experiments began with the entire system filled with conditioned tap water. The water treatment system was operated for each set of experimental conditions until steady state. Steady state was defined as when the floc blanket formed and reached the floc weir and the floc blanket suspended solids concentration (FBSC) was constant within 5% over 2 hydraulic residence times of the floc blanket. FBSC was measured using the image analysis technique described in Hurst et al. (2014b). Images for FBSC were collected every 60 seconds for the duration of each experiment. Turbidity readings were collected every 5 seconds.

Graphs presented below show the average steady state values (with standard deviation) of the parameter presented. All flocculators in Table 4 were tested on the water treatment system with a jet shear less than the average shear of the flocculator or “neutral” shear jet. This was to ensure that no floc breakup would occur between the flocculator and floc blanket sedimentation tank.

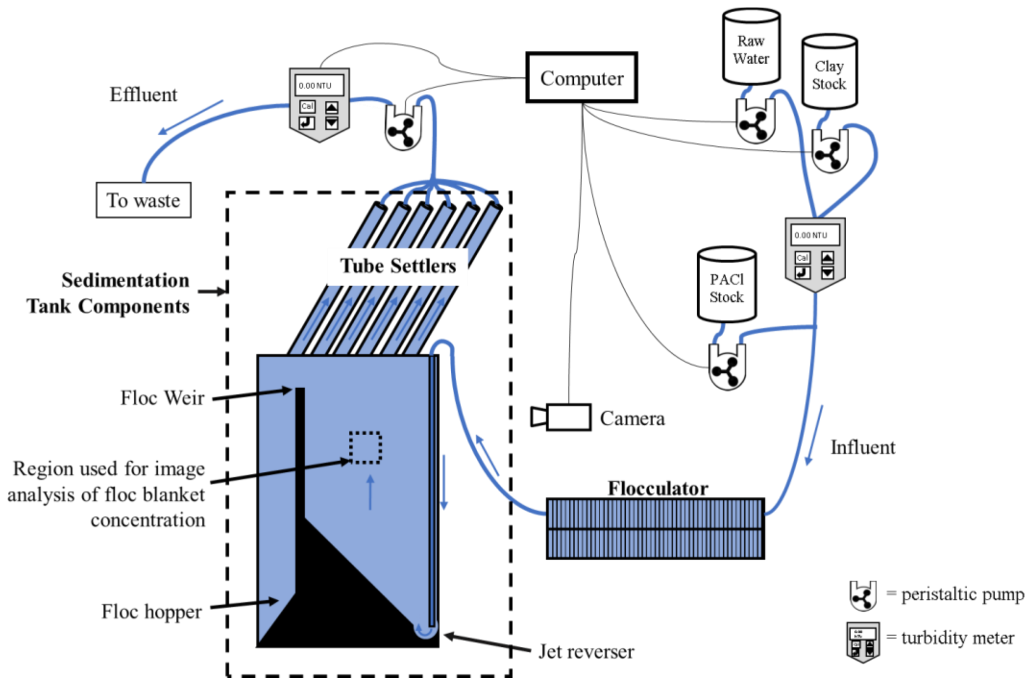

Figure 21. Experimental setup for water treatment system performance from Garland et al. (2017).

Residual particle aggregation model

The first hypothesis is that residual particles collide with other residual particles as they flow between the hindered flocs upward through the floc blanket. In this case, the role of the hindered flocs is to provide fluid shear to increase the collision rate of the residual particles. This hypothesized aggregation mechanism is identical to hydraulic flocculation with the only difference being the source of the fluid shear. During flocculation, it is postulated that the primary particles in the initial raw water suspension predominantly make collisions with other primary particles or small flocs. As flocculation proceeds and flocs grow, the total number of primary particles or small flocs decreases, particles become farther apart, and the time it takes for a collision to occur grows.

Settled water turbidity subsequent to flocculation that occurs under viscous (laminar flow) conditions can be predicted using the following model from Swetland et al. (2014):

$$pC^{*} = \log\left(\beta G \theta \Gamma \phi_0^{2/3}\right) \tag{2}$$

Where pC^{*} is defined as:

$$pC^{*} = -log\left(\frac{C_{Eff}}{C_{In}}\right) \tag{3}$$

Where G is the fluid velocity gradient, Γ is the fractional surface coverage by coagulant precipitates on clay particles, θ is the fluid residence time in the flocculator, ϕ_0 is the initial primary particle volume fraction, C_{Eff} is the settled effluent turbidity of the process, and C_{In} is the influent turbidity of the process. The β term is related to the size of particles in the initial suspension and the capture velocity of tube or plate settlers and is the model fitting parameter.

Equation 3 can be applied to the system at steady state and separate flocculator settled water experiments (as described below) can be used to identify performance values for the floc blanket in each process. Performance attributed to the floc blanket can be calculated by subtracting the performance of the flocculator settled water experiments (flocculator and tube settler processes) from the performance of system (flocculator, floc blanket and tube settler processes):

$$pC^*_{FlocBlanket} = pC^*_{System} - pC^*_{Flocculator} \qquad (4)$$

Where pC^*_{System} is the overall steady state system performance and $pC^*_{Flocculator}$ is the flocculator/tube settler performance in the absence of a floc blanket.

The first hypothesis was explored by creating a model for the flocculation of residual particles in the floc blanket. If the number of particles available for collisions leaving the flocculator remain unchanged and the floc blanket only provides additional $G\theta$ (G being much lower) then we could expect performance of the whole system (flocculator, floc blanket, and tube settlers) to be described by:

$$pC^*_{SysFlocculate} = \log\left[\beta\Gamma\phi_0^{2/3}(G_{Flocculator}\theta_{Flocculator} + G_{FB}\theta_{FB})\right] \qquad (5)$$

Where β is defined above and calibrated from the flocculator, ϕ_0 is the clay volume fraction for the initial raw water suspension, $G_{Flocculator}$ is velocity gradient for the flocculator, $\theta_{Flocculator}$ is the hydraulic residence time for the flocculator, G_{FB} is the velocity gradient created by the floc blanket, and θ_{FB} is the hydraulic residence time of the floc blanket.

Velocity gradient and hydraulic residence time of the floc blanket were determined from observation of head loss, floc blanket height, and floc blanket suspended solids concentration as follows:

The floc blanket is a fluidized bed of flocs whose head loss per unit of floc blanket depth is related to the height of the floc blanket and the density difference of the fluid and floc blanket is:

$$\frac{h_{LFB}}{H_{FB}} = \frac{\rho_{FB} - \rho_{H2O}}{\rho_{H2O}} \qquad (6)$$

Where h_{LFB} is the head loss through the floc blanket, H_{FB} is the height of the floc blanket, and ρ_{FB} is the density of the floc blanket. This analysis neglects the contribution of the coagulant because its density is close to that of water and the mass of coagulant is small compared with the mass of clay. The density of a floc blanket is then obtained from the volume weighted average of the density of clay and water.

$$\rho_{FB} = \frac{m_{H2O} + m_{Clay}}{V_{FB}} \qquad (7)$$

Where m_{H2O} is the mass of water in the floc blanket (kg), m_{Clay} is the mass of clay in the floc blanket (kg), and V_{FB} is the volume of the floc blanket (3.5 L in these experiments). The mass of clay in the floc blanket is calculated as:

$$m_{Clay} = C_{Clay}V_{FB} \qquad (8)$$

Where C_{Clay} is the concentration of clay in the floc blanket (kg/m^3) (determined by image analysis mentioned in the Methods section and described in full in Hurst et al, 2014a). Concentration measurements at various locations reveal the floc blanket approximately uniform, an observation also noted by other researchers (Su et al, 2004). The mass of water in the floc blanket is:

$$m_{H2O} = \left(1 - \frac{C_{Clay}}{\rho_{Clay}}\right)\rho_{H2O}V_{FB} \tag{9}$$

Combining equations 7, 8, and 9, the density of the floc blanket becomes:

$$\rho_{FB} = \left(1 - \frac{C_{Clay}}{\rho_{Clay}}\right)\rho_{H2O} + C_{Clay} \tag{10}$$

Combing equations 6 and 10, head loss through the floc blanket per unit length of the floc blanket can be described by:

$$\frac{h_{LFB}}{H_{FB}} = \left(\frac{1}{\rho_{H2O}} - \frac{1}{\rho_{Clay}}\right)C_{Clay} \tag{11}$$

The energy dissipation rate through the floc blanket based on head loss through the floc blanket is determined by Hurst et al. (2010):

$$\varepsilon = \frac{g h_{LFB}}{\theta_{FB}} \tag{12}$$

Where g is the gravitational constant. Residence time through the floc blanket is a function of the height of the floc blanket and can be described as (Bache, 2010):

$$\theta_{FB} = \frac{H_{FB}\varphi_{FB}}{V_{up}} \tag{13}$$

Where φ_{FB} is the porosity of the floc blanket and V_{up} is the upflow velocity of the sedimentation tank (1.2 mm/s in these experiments). Substituting equation 13 into equation 12 the following equation results:

$$\varepsilon = \frac{gV_{up}}{\varphi_{FB}} \frac{h_{LFB}}{H_{FB}} \tag{14}$$

The velocity gradient is related to the energy dissipation rate by (Bache, 2010; Hurst et al., 2010):

$$G_{FB} = \sqrt{\frac{\varepsilon}{\nu_{H2O}}} \tag{15}$$

Where ν_{H2O} is the viscosity of water ($1.004\text{x}10^{-6}$ m^2/s at $20^{o}C$). Equation 14 can be substituted into equation 15 to yield:

$$G_{FB} = \sqrt{\frac{gV_{up}}{\nu_{H2O}\varphi_{FB}} \frac{h_{LFB}}{H_{FB}}} \tag{16}$$

Finally, equation 16 can be combined with equation 11 to obtain:

$$G_{FB} = \sqrt{\frac{gV_{up}}{\nu_{H2O}\varphi_{FB}} \left(\frac{1}{\rho_{H2O}} - \frac{1}{\rho_{Clay}}\right) C_{Clay}} \tag{17}$$

The floc blanket porosity, φ_{FB}, is defined as $\varphi_{FB}=1-\phi_{FB}$ and the floc volume fraction, ϕ_{FB} was estimated using data from the settled floc blanket described below. The floc volume fraction of a fully developed floc blanket flocs was approximated using a modified version of the 30-min settled test (Gregory, 1979). After a floc blanket had formed and reached steady state, flow through the floc blanket was stopped and the floc blanket was allowed to settle for 30 minutes. The volume occupied by the settled floc blanket at 30 min ($Vol_{Settled}$) was determined using images and the known dimensions of the tank. For a packed bed of spheres, the void volume was found to be 0.4 (Dullien, 1991). After the floc blanket settled, flocs were approximated as spheres in a packed bed such that the volume occupied by flocs would be 0.6 times the bulk volume of the settled floc blanket. Flocs are frequently approximated as spheres (Sun et al, 2015, for example) and in the floc blanket, where collisions are abundant, the floc would have filled in with other flocs resulting in a more spherical floc. The floc volume fraction in the floc blanket is then:

$$\phi_{FB} = \frac{0.6 Vol_{Settled}}{V_{FB}} \tag{18}$$

ϕ_{Floc0} is determined as described by Swetland et al. (2014):

$$\phi_{Floc0} = \frac{C_{PACl}}{\rho_{PACl}} + \frac{C_{Clay}}{\rho_{Clay}} \tag{19}$$

Where C_{PACl} is the concentration of PACl in mg/L as Al, C_{Clay} is the concentration of clay in mg/L, and ρ_{PACl} is the density of PACl (1,138 mg/L). The coagulant coverage on the clay, Γ, in suspension (taking into account PACl adhering to the walls of the flocculator) can be determined as described by Swetland et al. (2014):

$$\Gamma = 1 - e^{-\frac{d_{Coag}^2}{SA_{Clay}} N_{perClay} R_{Clay}} \tag{20}$$

Where d_{Coag} is the average diameter of coagulant precipitate (m), SA_{Clay} is the total surface area of the clay (m^2), $N_{perClay}$ is the average number of coagulant precipitates per clay particle, and R_{Clay} is the fraction of coagulant particles that adhere to clay particles which is defined in Swetland et al. (2014). The PACl precipitate primary particle size (d_{Coag}) was determined using a Malvern Mastersizer Nano-ZS. A 138.5 mg/L solution of PACl as Al was sized and the diameter of primary PACl precipitates was determined to be 90 nm.

The third hypothesized mechanism for residual particle aggregation is that residual particles attach to hindered flocs. This mechanism could be described as a filtration mechanism and similar to clean bed filtration models (Tufenkji & Elimelech, 2004, equation 19) floc blanket performance, pC^*, would be predicted to be directly proportional to the depth of the floc blanket. This hypothesized mechanism requires that flocs with sedimentation velocities larger than the upflow velocity continue to grow until they reach terminal size (set by the shear conditions and coagulant coverage in the floc blanket).

Flocculator settled water turbidity

Experimental setups to obtain settled water turbidity for each flocculator are illustrated in Figure 22. Raw water at 100 NTU was mixed with PACl at 3 concentrations (0.625, 1.25, and 2.5 mg/L) and flocculated using coiled tube flocculators described above. Settled water turbidity of the flocculated water was found by extracting a sample (4 % of total flow) of the flocculated water (Figure 22) through a single tube settler with capture velocity of 0.1mm/s. Flow rate of the tube settler was controlled by a Masterflex peristaltic pump that pulled water through the tube settler.

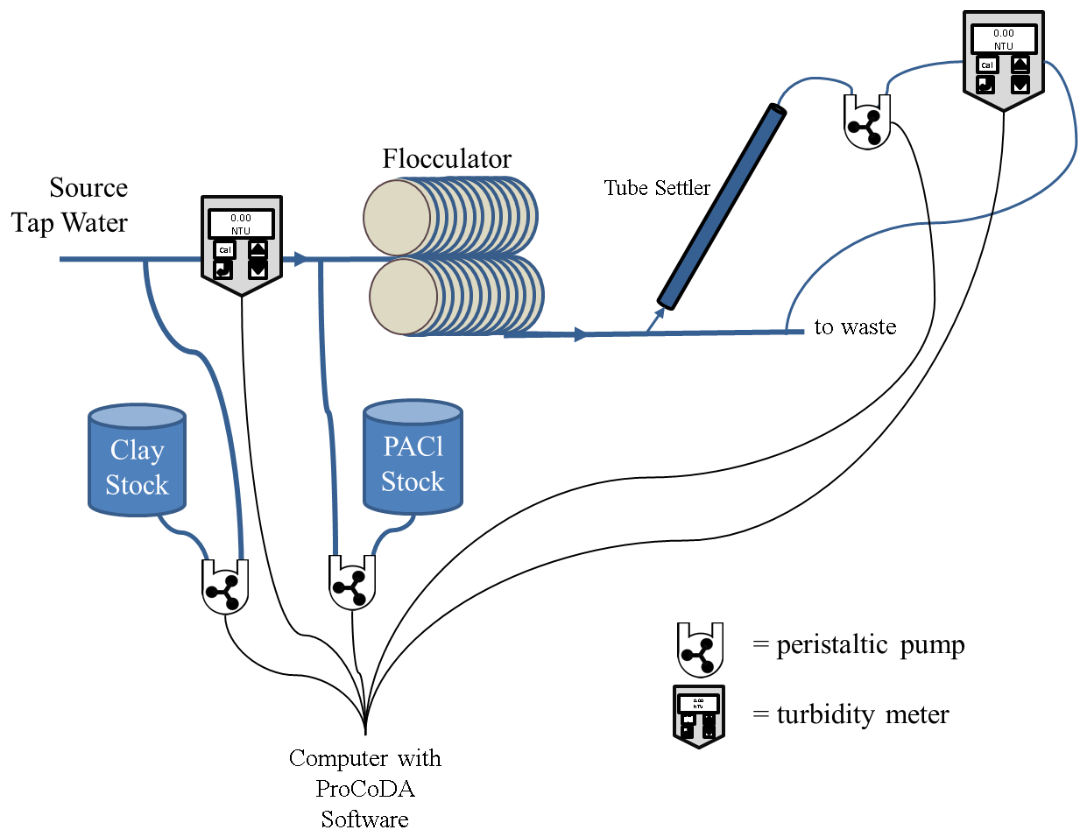

Figure 22 Experimental setup to acquire settled water turbidity in the absence of a floc blanket.

Floc volume fractions of the flocculator were found by using equation 19. The conversion from NTU to clay concentration was determined experimentally to be 1NTU≅1.7 mg/L which is similar to the 1.5 mg/L determined by Wei et al. (2015).

Results

Flocculator Settled Water Turbidity

Settled water turbidity for all flocculators decreased with increasing PACl surface coverage (Figure 23). PACl dose is presented as PACl surface coverage (equation 20) to account for loss to flocculator walls. Lower *G* flocculators (*G*=72 and 126 Hz) had lower settled water turbidity while high *G* flocculators (*G*=251 and 340 Hz) had high settled water turbidity. The flocculation model was fit to the two low *G*

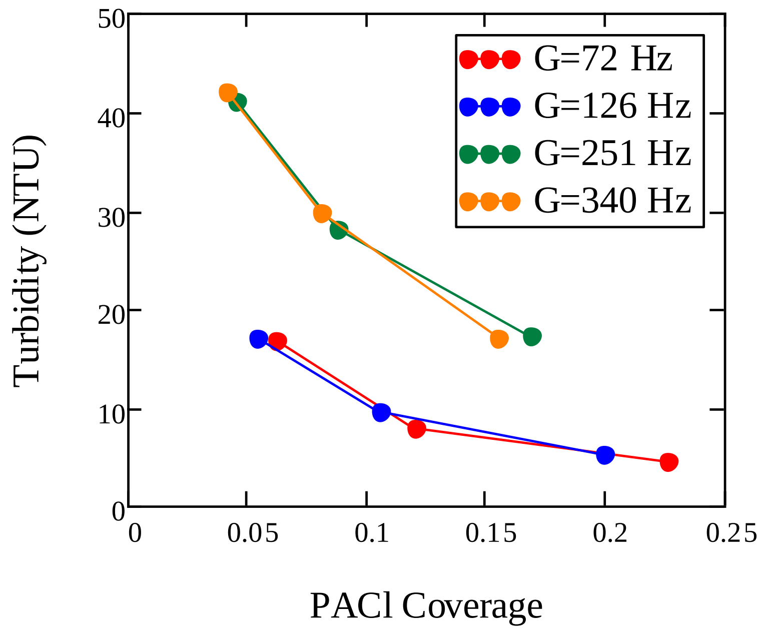

Figure 23. Settled water turbidity for all flocculators and PACl coverages tested.

flocculators with a β of 0.8. It is possible that the high *G* flocculators (with corresponding lower hydraulic residence times) had poorer performance because there was less time for diffusion to transport coagulant nanoclusters to clay surfaces.

Combined flocculator, floc blanket, and tube settler experiments

Two PACl coverages using the G=72 Hz flocculator were tested (the lowest and highest) but the jet reverser (see Figure 21) filled in with the density current of flocs sliding down the bottom slope of the sedimentation tank. The incoming jet was overtaken because the momentum of the density current of flocs flowing toward the jet reverser was higher than the momentum of the incoming jet. This is considered a failure at full scale because the floc blanket is unstable or may fail to form if the flocs are not reliably resuspended. The accumulation of sediment is also undesirable in the self-cleaning tank.

Settled water turbidity (i.e., excluding results for the 72 Hz experiments) for each flocculator and coverage tested are shown in Figure 24. With each flocculator, as the PACl dose increased, settled water turbidity decreased. Additionally, lower G (higher θ) flocculators produced lower settled water turbidity. Steady state FBSC decreased with increasing PACl coverages for all flocculators (Figure 25), a trend also seen in Su et al. (2004). Floc blanket increased slightly with increasing PACl coverage and was independent of the flocculator used in these experiments (Figure 26). Flocculator $G\theta$ for these experiments was ~20,000. Floc blanket performance likely would vary more dramatically if $G\theta$ were varied.

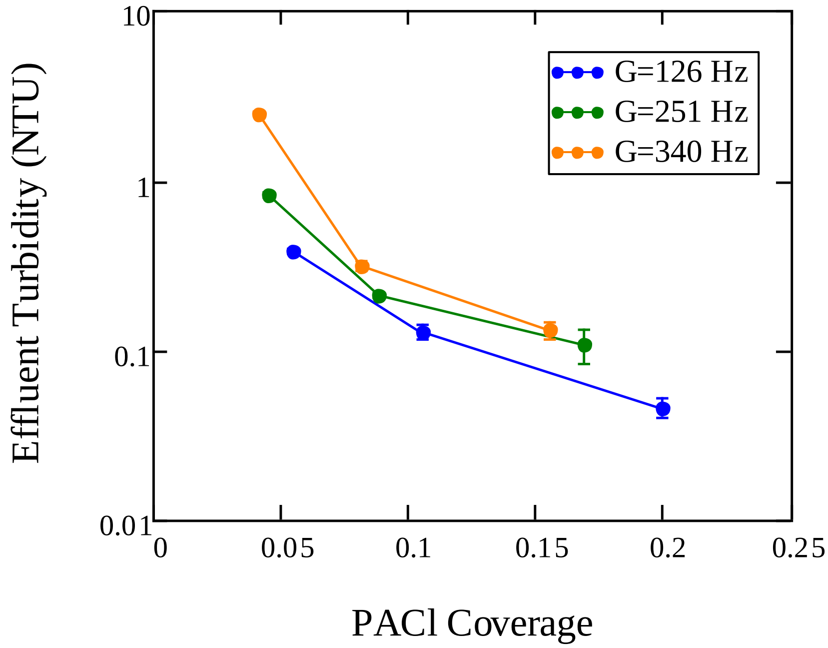

Figure 24. Combined flocculator, floc blanket, tube settler system settled water turbidity for all flocculators and PACl coverages tested. Standard deviation bars are shown for steady state effluent turbidity but are difficult to see as data points are a similar size.

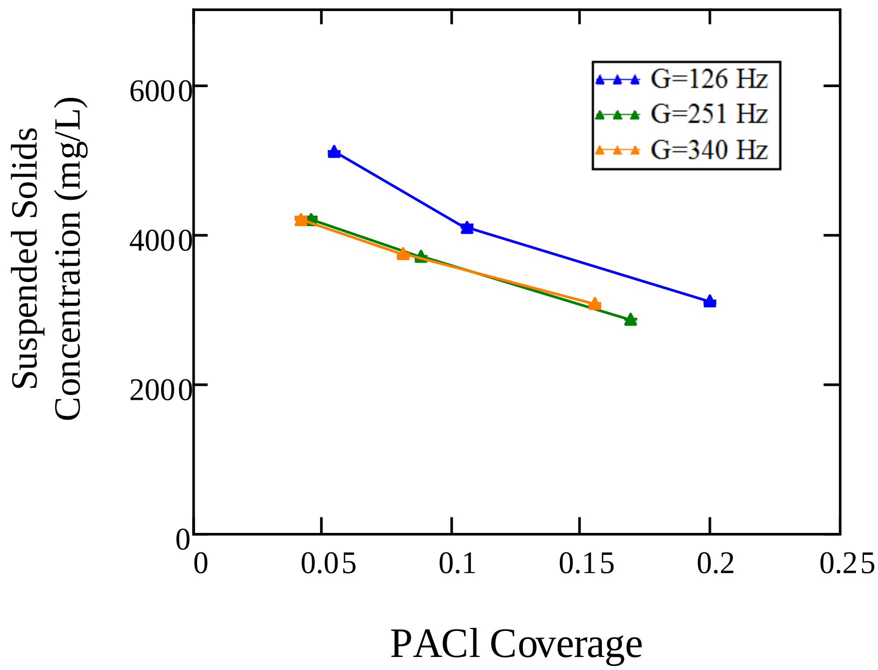

Figure 25. Steady state floc blanket suspended solids concentration for all flocculators and PACl coverages tested. Standard deviation bars are shown for steady state floc blanket suspended solids concentration but are difficult to see as data points are a similar size.

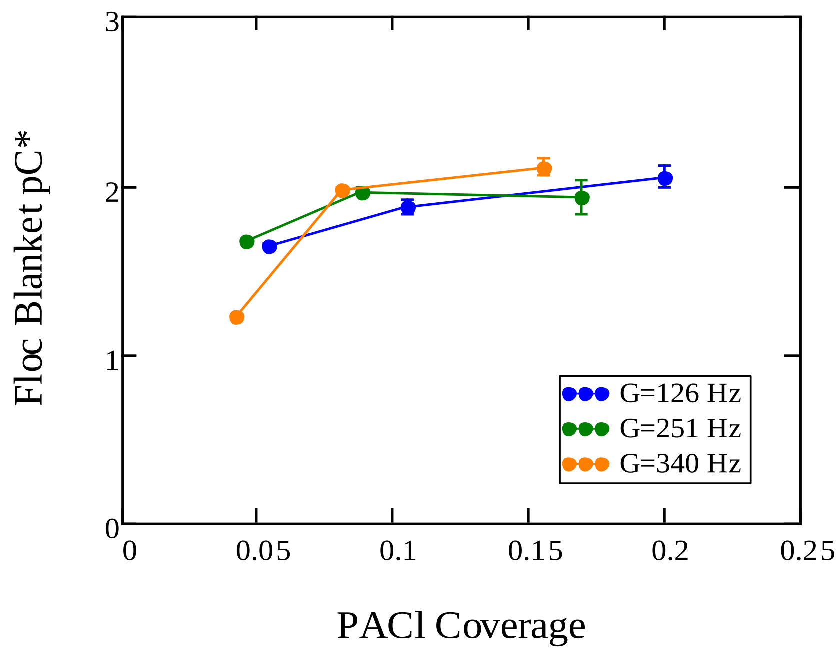

Figure 26. Steady state floc blanket performance for all flocculators and PACl coverages tested. Standard deviation bars are shown for steady state floc blanket suspended solids concentration but are difficult to see as data points are a similar size.

Flocculation model

If collisions with residual flocs only occur with other residual flocs (hypothesis 1) and the role of the floc blanket is only to provide more $G\theta$ (in addition to the $G\theta$ of the flocculator), the system would have performed much worse than was observed (Figure 27). The $G\theta$ provided by the floc blanket is approximately 3,400 (calculated by the product of equation 13 and 17). This $G\theta$ is a small fraction of the

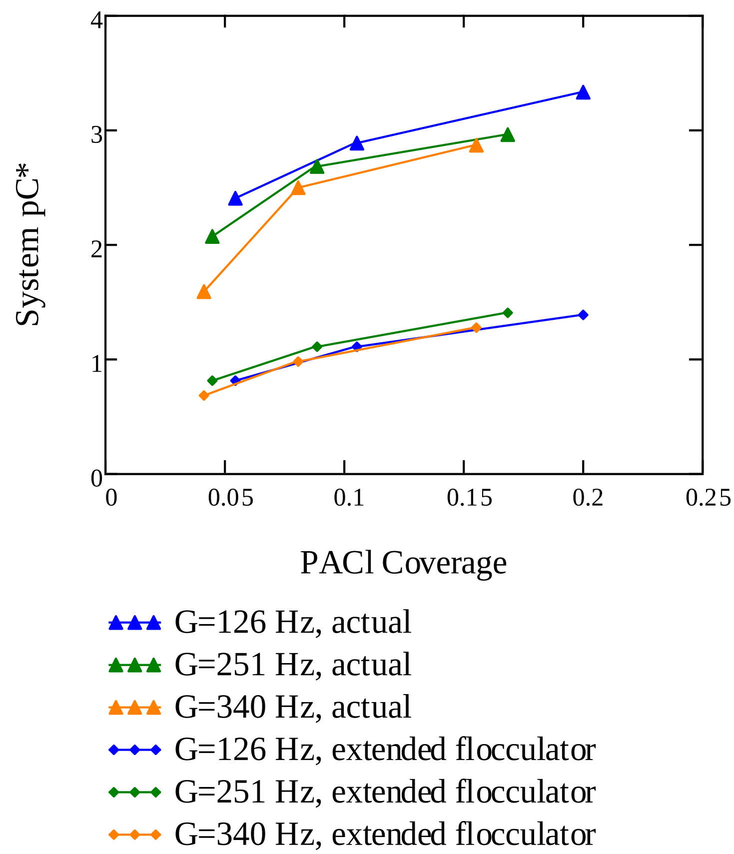

Figure 27. Comparison of actual system performance vs. predicted if floc blanket only provided additional Gθ (the floc blanket was an extended flocculator)

$G\theta$ of 20,000 provided by the flocculator and thus the dramatic performance improvement created by the presence of the floc blanket cannot be explained by this additional $G\theta$. The improved performance in the presence of a floc blanket indicates that collisions with larger flocs also must be occurring (hypothesis 2 or 3).

Hypothesis 3 (residual particles aggregate with terminal flocs) was tested by comparison with filtration model predictions. The change in floc blanket performance during floc blanket growth above the sloped bottom at PACl dose of 2.5 mg/L PACl as Al for all flocculators is shown in Figure 28. As the floc blanket increases in height, performance initially increases linearly with height but then begins to asymptotically approach a maximum pC^*. The initial increase in performance with depth is approximately linear as predicted by the filtration model. However, once floc blanket depth exceeds ~70 cm, performance is non-linear with depth. It is possible that as the floc blanket forms and the flocs in the floc blanket collide and increase in size, flocs will begin to reach terminal size. Other researchers and results in this paper suggest that a terminal size, residual particles have very low collision efficiencies with the large, terminal flocs and thus an increasing number of flocs become effectively inert. The increase in floc blanket height after this point could be a result of accumulated terminal (effectively inert) flocs and, as a result, additional increase in the floc blanket depth (beyond a given height) is not expected to result in a significant performance improvement.

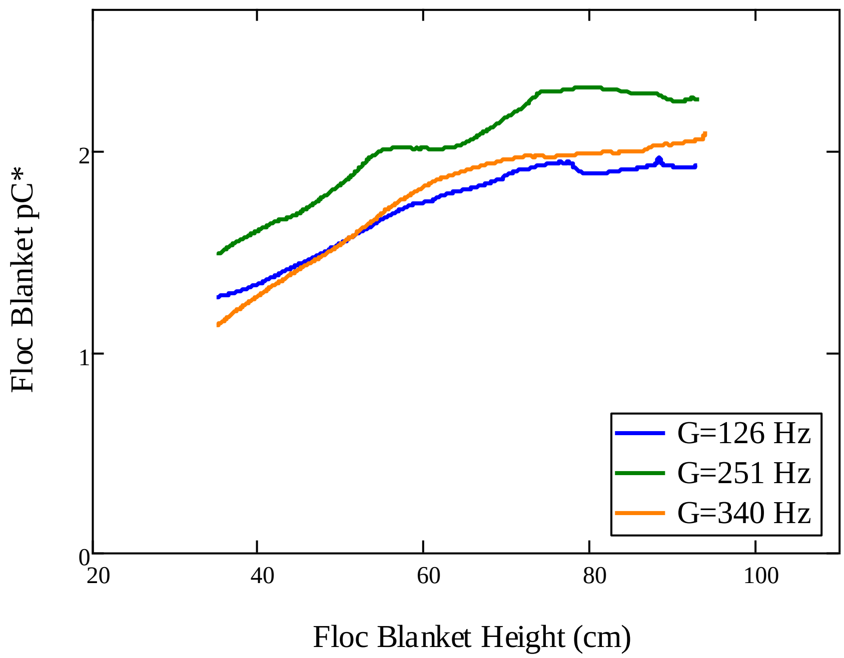

Figure 28. Floc blanket pC* vs. height during formation for all flocculators at 2.5 mg/L PACl as Al. Data shown is only for after the floc blanket interface height is above the bottom hopper and data was smoothed over 30 minutes.

Discussion

Floc blanket performance is not explained by the additional $G\theta$ for collisions between residual particles (equation 5 and Figure 27). Therefore, hypothesis 1 is not sufficient to explain the data. Floc blanket performance does not increase linearly with depth throughout the growth of the floc blanket. Based on these results, hypothesis 3 was not disproved but should be divided into 2 subcategories: 3a) residual flocs make collisions with *all* hindered flocs and 3b) residual flocs make collisions with a fraction of hindered flocs that have not reached terminal size. Given that performance did not increase linearly with depth until the floc blanket reached the floc weir, option 3a can be ruled out (Figure 28). In the filtration regime, an increase in filter material (flocs in this case) would necessitate increased removal which was not observed. Under hypothesis 3b, the linear increase in performance with depth is attributed to a large number of fresh, hindered flocs that have not reached terminal size. As terminal flocs 'fill up' with residual particles, the capacity to make a successful collision with a residual particle decreases and there is no longer a linear increase in performance with depth. It is possible that terminal flocs act as collector flocs to residual particles; however, this mechanism is not supported by the findings of previous researchers who concluded that the collision efficiency between flocs that vary greatly in size is very small (Adler, 1981; Han & Lawler, 1992; Veerapaneni & Wiesner, 1996; Xiao et al, 2013). It is possible that the large number of terminal flocs in the floc blanket may ameliorate the reduced collision efficiency to some extent.

The remaining hypothesis is that residual particles are attaching to transitional flocs. Transitional flocs are closer than hindered flocs in size to residual particles and thus they would be expected to be the more favorable for collisions. Transitional flocs may be concentrated in the floc blanket by lamellar sedimentation. Transitional flocs can only leave the floc blanket by being wasted over the floc weir or by growing to the hindered category (when the capture velocity of the floc reaches or exceeds the upflow velocity). The rate of conversion from transitional to hindered increases with the concentration of transitional flocs. At steady state, the rate that transitional flocs enter the floc blanket (by being imported into the floc blanket from the flocculator plus the rate that they are formed from the collision of residual particles) must match the rate that transitional flocs leave the floc blanket (wasted over the floc weir) plus the rate at which they are converted to hindered flocs.

The initial increase in performance with floc blanket depth (Figure 28) can be explained under hypothesis 2 and 3b. If hypothesis 2 is correct, performance may be explained by a gradual increase in the concentration of transitional flocs as they are returned from the tube settlers to the floc blanket. Transitional flocs form density currents that flow from the tube settlers down to the floc blanket. Although the transitional flocs have individual sedimentation velocities that are smaller than the fluid upflow velocity, they form a high concentration density current that is able to fall back to the floc blanket. It is not clear if transitional flocs that are mixed into the floc blanket are quickly returned by the tube settlers given their low sedimentation velocity.

If hypothesis 3b is correct, the initial performance would be attributed to a large portion of terminal flocs (that have not reached terminal size set by the floc blanket shear) acting as collectors for residual particles. As the experiment proceeds, performance levels off because some of the hindered flocs acting as collectors reach terminal size and become inert.

If hypothesis 2 is correct, the concentration of small transitional flocs (and hence the rate of collisions with residual particles) could be increased by either breaking the flocs in a high shear zone as they enter the floc blanket or by operating the flocculator at a higher G. Floc break up in a high shear zone was explored previously (Garland et al., 2016) and the results indicate that floc blanket performance is largely independent of the shear intensity at the entrance to the floc blanket up to a maximum of 300 mW/kg or 550 Hz. It is possible that floc breakup produces both residual particles and smaller transitional flocs and the net result is an insignificant change in performance.

Increasing the flocculator shear (at approximately constant $G\theta$) was evaluated in this research and the net result was a small reduction in system performance. It is possible that the very high rate flocculators that were investigated here had hydraulic residence times too low to provide time for the coagulant precipitate to be completely transported to primary particle surfaces. If coagulant precipitate transport in a 100 NTU kaolin clay suspension requires more than 1 minute, then clay could be traveling through the flocculator in less time than it takes for the coagulant precipitate to attach to the clay. This reduced surface coverage of residual particles could explain the poorer performance of the high G flocculators as shown in Figure 23. It is possible that the particle size distribution exiting the flocculator could provide additional insights. Quantifying flocculated particle size distributions is a topic of ongoing research by the authors.

In system performance runs with G=72 Hz flocculator and neutral G jet, the inlet jet was overtaken by the density current moving into the jet reverser before a floc blanket had fully developed. For operational and design guidelines, prevention of this failure is achieved by ensuring the momentum of the inlet jet exceeds the momentum of the density current by maintaining a high jet velocity.

Summaries

- Three hypotheses explaining the aggregation of non-settleable (residual) particles by floc blankets were evaluated using a flocculator, floc blanket, and tube settler water treatment train. Residual particle concentrations are too low to have significant aggregation. Transitional flocs may aggregate with residual particles because the concentration of transition flocs may be increased by return from lamellar sedimentation.
- Lack of a linear relationship between pC^* and floc blanket height during the entire growth of the floc blanket contradicts filtration-like behavior that would occur if all flocs in the floc blanket served as collectors. It remains possible that hindered flocs act as collectors with limited capacity to capture residual particles (due to shear limiting the maximum size of the hindered flocs or due to a reduction in floc permeability as residual particles attach).
- High inlet jet momentum is required to prevent sludge accumulation in the bottom of the sedimentation tank preventing anaerobic activity and facilitating hydraulic removal of suspended solids.
- Future studies should measure floc sizes throughout flocculator, floc blanket, and lamellar sedimentation systems.

Acknowledgments

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Bibliography

Adachi, Y., & Tanaka, Y. (1997). Settling velocity of an aluminum-kaolinite floc. *Water Research*, 31(3), 449.

Adler, P. M. (1981). Heterocoagulation in shear flow. *Journal of Colloid and Interface Science*, 83(1), 106–115.

AWWA/ASCE. (2012). Water Treatment Plant Design (5th ed.). American Water Works Association & American Society of Civil Engineers, McGraw-Hill.

Bache, D. H. (2010). Model of dynamic and macroscopic features of a floc blanket. *Journal of Water Supply: Research and Technology—AQUA*, 59(1), 53.

Bache, D. H., & Gregory, R. (2010). Flocs and separation processes in drinking water treatment: a review. *Journal of Water Supply: Research and Technology—AQUA*, 59(1), 16.

Cornell University Water System. (2016). Drinking Water Quality Report. Ithaca, NY.

Dullien, F. A. (1991). Porous Media: Fluid Transport and Pore Structure (2nd ed.). Academic Press.

Garland, C., Weber-Shirk, M., & Lion, L. W. (2016). Influence of Variable Inlet Jet Velocity on Failure Modes of a Floc Blanket in a Water Treatment Process Train. *Environmental Engineering Science*, 33(2), 79–87.

Garland, C., Weber-Shirk, M., & Lion, L. W. (2017). Revisiting hydraulic flocculator design for use in water treatment systems with fluidized floc beds. *Environmental Engineering Science*, 34(2), 122–129.

Gregory, R. (1979). Floc Blanket Clarification. Technical Report.

Han, M., & Lawler, D. F. (1992). (Relative) insignificance of G in flocculation. *Journal / American Water Works Association*, 84(10), 79–91.

Hurst, M., Weber-Shirk, M. and Lion, L.W. (2010). Parameters affecting steady-state floc blanket performance. *Journal of Water Supply: Research and Technology—AQUA*. 59(5), p.312.

Hurst, M., Weber-Shirk, M., Charles, P., & Lion, L. W. (2014a). Apparatus for observation and analysis of floc blanket formation and performance. *Journal of Environmental Engineering*, 140(1), 11–20.

Hurst, M., Weber-Shirk, M., & Lion, L. W. (2014b). Image analysis of floc blanket dynamics: investigation of floc blanket thickening, growth, and steady state. *Journal of Environmental Engineering*, 140(4), 1–10.

Process Control and Data Acquisition (ProCoDA). (2015). Retrieved from: https://confluence.cornell.edu/display/AGUACLARA/ProCoDA

Su, S. T., Wu, R. M., & Lee, D. J. (2004). Blanket dynamics in upflow suspended bed. *Water Research*, 38(1), 89–96.

Sun, S., Weber-Shirk, M., & Lion, L. W. (2015). Characterization of flocs and floc size distributions using image analysis. *Environmental Engineering Science*, 33(1), 25–34.

Swetland, K. A., Weber-Shirk, M. L., & Lion, L. W. (2014). Flocculation-sedimentation performance model for laminar-flow hydraulic flocculation with polyaluminum chloride and aluminum sulfate coagulants. *Journal of Environmental Engineering*, 140(3), 4014002.

Tambo, N., & Hozumi, H. (1979). Physical Aspect Of Flocculation Process--II . Contact Flocculation. *Water Research*, 13, 441–448.

Tambo, Norihito, and Yoshimasa Watanabe. 1978. "Physical Characteristics of Flocs-I. The Floc Density Function and Aluminum Floc." *Water Research* 13: 409–19.

Tufenkji, N., & Elimelech, M. (2004). Correlation equation for predicting single-collector efficiency in physiochemical filtration in saturated porous media. *Environmental Science & Technology*, 38(2), 529–536.

Veerapaneni, S., & Wiesner, M. (1996). Hydrodynamics of fractal aggregates with radially varying permeability. *Journal of Colloid and Interface Science*, 177(1), 45–57. http://doi.org/10.1006/jcis.1996.0005

Weber-Shirk, M. L., & Lion, L. W. (2015). Fractal models for floc density, sedimentation velocity, and floc volume fraction for high peclet number reactors. *Environmental Engineering Science*, 32(12), 978–982. http://doi.org/10.1089/ees.2015.0302

Wei, N., Zhang, Z., Liu, D., Wu, Y., Wang, J., & Wang, Q. (2015). Coagulation behavior of polyaluminum chloride: Effects of pH and coagulant dosage. *Chinese Journal of Chemical Engineering*, 23(6), 1041–1046.

Xiao, F., Lam, K. M., & Li, X. (2013). Investigation and visualization of internal flow through particle aggregates and microbial flocs using particle image velocimetry. *Journal of Colloid and Interface Science*, 397, 163–168. http://doi.org/10.1016/j.jcis.2013.01.053

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

The novel apparatus used in this research has proven to be vital to furthering our understanding of the floc blanket and how other processes (namely flocculation and lamellar sedimentation) impact it. Conditions and operational parameters on the apparatus can be easily adjusted and tested and processes observed with ease. In this research, suggested design parameters for jet inlet velocity, flocculator residence time, and flocculator *G* were challenged and results suggested that current guidelines are not optimal.

Aside from lowering effluent turbidity, one of the key roles of the floc blanket in AguaClara designs is to continually transport suspended solids into the floc hopper and consolidate sludge without mechanized equipment. This is achieved by ensuring that no settling occurs in the bottom of the sedimentation tank by having the inlet jet resuspend the density current of settled solids traveling into the jet. A range of inlet jet velocities were tested on the apparatus and results suggest that a large jet velocity (340 mm/s) could be used before a deterioration in performance is seen. This value is much higher than the suggested 10 to 25 mm/s by design guidelines. Before the limiting jet velocity is reached, however, it is likely that flocs are being broken at the interface where the inlet jet and density current interact. Given that performance did not decrease, the broken flocs either reformed in the floc blanket or were large enough to be captured by the tube settlers.

Design guidelines for water treatment facilities are based on empirical values and not on optimized designs. Processes that can be designed with fewer materials and reduced areas would considerably lower capital costs which could potentially be done without sacrificing performance. Seven flocculators as large as or smaller than design guidelines were tested on the apparatus to determine the effect on performance. In experiments with constant $G\theta$ (varying G and θ proportionally), the higher G (shorter θ) flocculator produced the lowest effluent turbidity even though the G used exceeded recommended design guidelines. When G is maintained and the residence time varied, minimal increase in effluent turbidity (0.42 NTU) occurred over a 62-fold reduction in residence time. Based on these results, smaller hydraulic flocculators (in conjunction with a floc blanket and tube settlers) could be used in water treatment plant designs without decreasing performance.

The mechanisms utilized in the floc blanket that result in reduced residual turbidity have been postulated by researchers but never proven. Based on floc size and time-scale, three categories of flocs (residual particles, transitional, and hindered flocs) were presented to characterize floc interactions in the floc blanket. Three hypotheses explaining the removal mechanism of residual flocs were analyzed: residual particles make collisions with 1) other residual particles, 2) small flocs, 3) floc blanket flocs. Results suggest that residual particles are likely making collisions with transitional flocs but further validation is needed. Confirming the presented hypotheses of floc-particle interactions will need to be done by examining floc sizes in the floc blanket.

Taking full advantage of the floc blanket will require that the removal mechanism of residual particles is well understood. It is clear that not all flocs in the floc blanket are directly active in providing collisions with residual particles (they may indirectly induce collisions by mixing) and that there is an exchange of flocs between size categories. The rates of formation (entering the category by transport from the flocculator or collisions with other flocs) and graduation (leaving the category by transport over the floc weir or the tube settlers, or collisions with other flocs) in each of these categories will be paramount to not only modeling floc blanket performance but also in being able to predict performance over a range of conditions. If we can model floc blanket performance based on influent floc size distributions, we can predict performance with changing influent turbidity and optimize performance by designing the flocculator to produce a given floc size distribution.

To get formation/graduation rates of floc categories, floc sizes throughout the system need to be verified. At this point, we are only able to collect floc sizes entering the floc blanket from the flocculator, exiting the floc weir, and potentially in the supernatant below the tube settlers and exiting the tube settlers. To the knowledge of the author, a non-invasive method of collecting floc sizes in the floc blanket does not exist but should be explored.

A source of flocs active in reducing residual turbidity is hypothesized to be the tube settlers. To confirm this, the performance of the floc blanket with and without the tube settlers contributing flocs to the floc blanket could be tested. In the case without tube settler contribution, one tube settler would still need to be operated to collect settled water turbidity and this tube settler should be oriented to direct any returned flocs to the floc hopper. The floc size distribution between the floc-water interface and the tube settlers should be collected through the duration of each experiment both with and without tube settler contribution. Flocs that are present in the supernatant with all tube settlers contributing minus flocs present when no tube settlers are contributing will be the flocs that are returned by the tube settlers. Comparing the effluent turbidity between the two experiments (all vs no tube settlers contributing) would demonstrate whether flocs returned by the tube settler are significant in reducing effluent turbidity. The experiments could be repeated with various growth conditions (changing coagulant dose or flocculator residence time as these were shown to change the rate of floc blanket formation).

Another parameter that could be increasing collisions with residual particles in the floc blanket is the step reduction in shear (G) from the flocculator. In tapered flocculation, a suspension is mixed at progressively lower G values in a step-wise manner. Presumably (but never verified) the progressively decreasing shear of the flocculator lowers the velocity gradient around flocs that allows for collisions that would have previously been limited by shear (i.e. collisions between relatively large and small flocs/particles). In the water treatment train examined, a suspension goes through a G of the flocculator and then a much lower G in the floc blanket, akin to tapered flocculation. To determine if the performance of the floc blanket can be explained by tapered flocculation, the floc blanket could be replaced with a flocculator with an equivalent $G\theta$ of the floc blanket. A tube settler should extract a portion of the suspension after the floc blanket equivalent flocculator to measure the settled water turbidity for performance comparison. Additionally, the floc blanket fluid residence time should be confirmed through dye tests to verify floc blanket hydraulic residence time. Results from these experiments should show whether the presence of a floc blanket creates tapered flocculation or of another mechanism is controlling performance. These experiments would not include the contribution from the tube settler, if determined to be significant from experiments described in the previous paragraph. If performance without tube settler contribution is the same as with equivalent floc blanket $G\theta$ flocculator, then the floc blanket acts as the final stage of tapered flocculation.

To advance to a place where the design of a water treatment plant can be optimized for performance and cost, accurately modeled processes based on proven mechanisms is paramount. It is clear from the research presented here that systems can operate outside of design guidelines without deteriorating (and in some cases improving) performance. The literature on water treatment is often difficult to assess and compare due to the highly varying methods and experimental setups used to conduct research. Consistency in research methodology is needed to advance knowledge of water treatment processes and how these processes influence each other to develop process model leading to optimized plant designs.

Determining $\Pi_{PlaneJet}$

The coefficient used for a plane jet, $\Pi_{PlaneJet}$, was determined using 2-D simulations on hydraulic flocculators. Hydraulic flocculators are designed such that flow travels around a series of baffles to create mixing (Figure 29). The flow around a baffle is a plane jet and simulations were used to determine $\Pi_{PlaneJet}$ for use in determining sedimentation tank inlet jet energy dissipation rate.

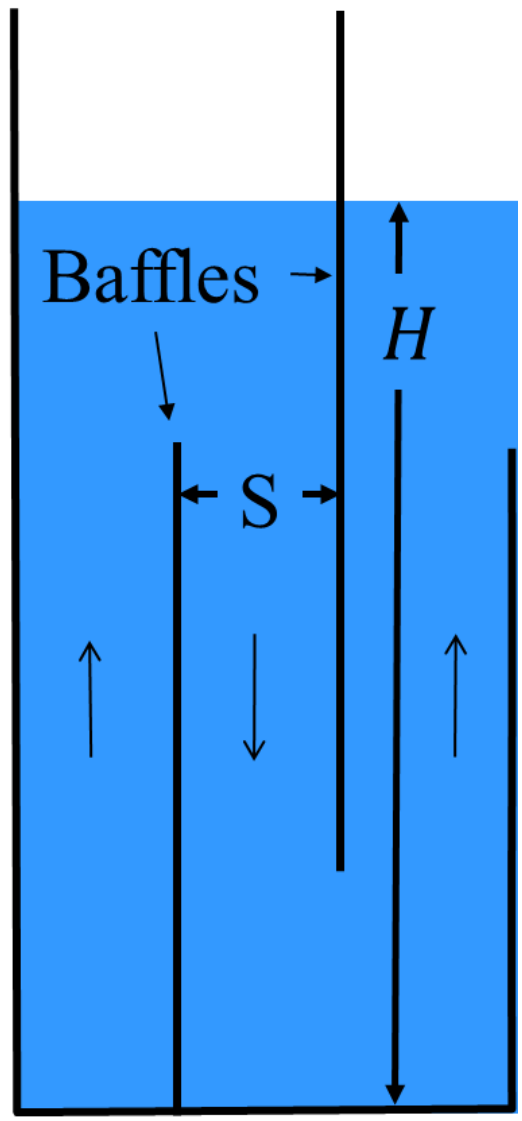

Figure 29. Schematic of hydraulic flocculator with relevant parameters.

Ideal flocculator design would have uniform shear (G) and, therefore, uniform energy dissipation rate. The flocculator efficiency can then be described as

$$\alpha_e = \frac{\varepsilon_{Max}}{\bar{\varepsilon}} \qquad (21)$$

As flow travel around the end of a baffle, a plane jet is formed that expands in the channel. Maximum energy dissipation rate for a plane jet is described as (adapted from Baldyga et al, 1995)

$$\varepsilon_{Max} = \frac{(\Pi_{JetPlane} V_{Jet})^3}{S_{Jet}} \tag{22}$$

and

$$V_{Jet} = \frac{\bar{V}}{\Pi_{VCBaffle}} \tag{23}$$

$$S_{Jet} = S\Pi_{VCBaffle} \tag{24}$$

$\bar{V}$ is the average velocity in the channel (*Q/SW*), *W* is the width of the channel (dimension perpendicular to view in Figure 29), and $\Pi_{VCBaffle}$ is the vena contracta coefficient around a 180° bend (0.62^2 or 0.384; Falkovich, 2011).

The average energy dissipation rate is the energy lost per unit time. Energy loss due to wall friction is negligible so that only minor loss due to the fluid contraction is significant. Average energy loss through the channel is described using minor loss

$$\varepsilon_{TotalperChannel} = K_e \frac{\bar{V}^2}{2} \tag{25}$$

Where K_e is the minor loss coefficient (2.64 determined by Stanislaus and Southern, 2010). To get average energy dissipation rate, $\varepsilon_{TotalperChannel}$ is divided by time required for the jet to travel through the channel resulting in

$$\bar{\varepsilon} = K_e \frac{\bar{V}^2}{2} \frac{1}{\theta_B} \tag{26}$$

Where θ_B is the plug flow residence time $(H/\bar{V})$. When $H/S<5$ values for α_e = 2 (Haarhoff and Van Der Walt, 2001). When $H/S>5$, α_e is calculated by substituting equation 22 and 26 into 21, yielding

$$\alpha_e = \frac{\Pi_{JetPlane}{}^3 2H}{\Pi_{VCBaffle}{}^4 K_e S} \tag{27}$$

Solving equation 27 for $\Pi_{JetPlane}$ gives the following results

$$\Pi_{JetPlane} = \left(\alpha_e \Pi_{VCBaffle}{}^4 \frac{K_e S}{2H}\right)^{1/3} \tag{28}$$

With H/S of 5 and a α_e of 2, equation 28 is solved to yield a $\Pi_{PlaneJet}$ value of 0.225.

Bibliography

Baldyga, J., Bourne, J. R., & Gholap, R. V. (1995). The influence of viscosity on mixing in jet reactors. *Chemical Engineering Science*, *50*(12), 1877–1880.

Daugherty, R. L. and Franzini, J. B. (1965). *Fluid Mechanics*, 6th ed. New York: McGraw-Hill. pp. 338-349.

Falkovich, G. (2011). Fluid Mechanics - A Short Course for Physicists. Cambridge University Press. Available online at: http://app.knovel.com/hotlink/toc/id:kpFMASCP01/fluid-mechanics-short/fluid-mechanics-short

Haarhoff, J. and Van Der Walt, J.J. (2001). "Towards Optimal Design Parameters for around-the-End Hydraulic Flocculators." *Journal of Water Supply: Research and Technology - AQUA* 50 (3): 149–59.

Stanislaus, T. and Southern, S. (2010). Validating computational fluid dynamics in ANSYS Fluent. Retrieved from: https://confluence.cornell.edu/display/AGUACLARA/Spring+2010+CFD+Flocculator+Simulation+Validations