The Effect of Floc Roll-up on Clay-Aluminum Hydroxide Flocs

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Abstract

Inclined plate and tube settlers are commonly used to create compact sedimentation tanks. Conventional design guidelines are based on obtaining a desired sedimentation design capture velocity. Theoretically, this capture velocity can still be achieved while greatly reducing conventional plate spacing or tube diameter. The greatest concern with small plate spacing is the danger of settling sludge being swept out with the finished water. This research presents the basis of this failure mechanism as high velocity gradients present at small tube settler diameters and small plate settler spacings.

Keywords: fractal dimension, capture velocity, plate settler, floc roll-up, floc rollup, tube settler, PI ratio, velocity gradient, sedimentation

Nomenclature

D d	lamellar spacing (L)
L l	length of settler (L)
V_c	design capture velocity for settlers (L/t)
Q	flow rate through one settler (L^3/t)
$V_{\uparrow}$ $V_{\uparrow Plate}$	upflow velocity through one settler (L/t)
α	angle of inclination
V_α V_α	approach velocity (L/t)
V_T	terminal velocity of a floc (L/t)
$V_{cRollup}$	capture velocity (L/t)

v_z	velocity profile in a settler (L/t)
d_{Floc}	diameter of a floc (L)
d_{Floc_0}	diameter of colloidal particles (L)
$D_{Fractal}$	fractal dimension of flocs
Φ	shape factor for flocs
υ	kinematic viscosity (L^2/t)
g	gravitational acceleration (L/t^2)
ρ	density (M/L^3)
L_e	entrance region length (L)
Re	Reynolds number
h_L	head loss (L).
θ	hydraulic residence time (t)
G	velocity gradient (1/t)
ϕ_{Floc_0}	floc volume fraction
ε	energy dissipation rate (ML^2/t^3)

Introduction

Lamellar sedimentation is one of the most widely used processes in water treatment, and as such, there is much research on the determining optimal configurations for lamellar systems. However, one parameter that has been under-studied is plate settler spacing. A review of existing documentation reveals suggested spacing in the range of 1.3 cm - 0.3 m based on empirical evidence; however, little to no theoretical backing has provided. Particularly, there has been no exploration of how local flow conditions affect particle capture. Letterman (1999) recommends a spacing of 0.3m for vertical-flow sedimentation tanks with a floc blanket and asserts that widely spaced plate settlers are more cost-effective in floc blanket clarifiers; however, no detailed analysis was presented. In contrast, Ziolo (1996) recommended a 0.05 m spacing for "ordinary" performance and loosely indicated that spacing could be adjusted based on the influent solids concentration. Ziolo and others have characterized performance in terms of the ratio of plate length to center-to-center spacing (L/D). Generally, improved plate settler performance was correlated with higher length to diameter ratios. Yao (1970) reported that good performance was achievable for length to spacing ratios between 20 and 40. Beyond a ratio of 40, there were diminishing returns in terms of performance for length of lamella added. However, Hansen and Culp (1967) experimentally found spacings in circular tubes as low as 1.3 cm could achieve up to a 96 percent reduction in turbidity, a significantly lower spacing than Ziolo's findings. Willis (1978) indicated that the greatest concern for small plate spacing is the danger of high velocities sweeping settling sludge out with finished water. Willis addressed this concern by designating the maximum tube loading as 1.70 mm/s, a tube settler design rate that "has proven reasonably satisfactory" in field applications. However, visual observation along with detailed laboratory studies have shown that high velocity gradients rather than the tube velocities cause settling flocs to be rolled up inclined lamella. This means that it is possible have tube velocities greater than 1.70 mm/s as long as the velocity gradients are kept to a minimum. This research presents initial studies on the quantitative relationship between velocity gradients, plate spacing, and performance. The theoretical effects of variable water chemistry on floc characteristics are explored and presented alongside experimental studies with a controlled clay aluminum hydroxide system.

Reducing plate spacing would decrease the cost of water treatment by allowing for smaller sedimentation tanks. The economic benefit of reduced plate spacing is particularly evident when considering the affordable access of safe drinking water to resource poor communities. The following example depicts the possible material savings on sedimentation tanks by halving plate spacing. The length of the plate settlers is typically about 20 times as long as the spacing. Conventional guidelines suggest a spacing of 5 cm, resulting in plate lengths of approximately 1 m. Assuming an angle of inclination of 60° for self-cleaning, these plate settlers would occupy 0.86 m of sedimentation tank depth. Reducing the spacing to 2.5 cm would reduce the required sedimentation tank depth by 0.43 m and cost of construction. This study was initiated to determine the practical extent to which plate settler spacing or tube diameter can be minimized.

Particle capture by Lamella

The experimental testing was performed on tube settlers rather than plate settlers because tubes were easier to implement at the laboratory scale. However, our general observations regarding failure modes are also applicable to lamellar plates. The design capture velocity of tube settlers in which the ends of the tube are perpendicular to the axis of the tube is given by (Shultz 1984) equation 1.

$$V_c = \frac{V_{\uparrow}}{\frac{L}{D}\cos\alpha\sin\alpha + \sin^2\alpha} \tag{1}$$

where L is the length of the tube settlers, D is the tube diameter, $V_{\uparrow}$ is the average vertical component of the fluid velocity in the tubes, and V_C is the terminal velocity of the slowest settling particle that is reliably captured by the tube settler.

Equation 1 illustrates that tube settler performance (as manifested by V_c) is maintained as long as the ratio of L/D is constant for a fixed $V_{\uparrow}$. Thus, it is theoretically possible to reduce L by decreasing the diameter of the tube settlers, D.

After a floc settles on the lower surface of a plate or a tube it continues to experience an upward drag caused by the fluid flow. The velocity at the centerline of the floc increases if the spacing between plates or the diameter of the tube is decreased while maintaining a constant average fluid velocity. Gravitational force will cause flocs to roll or slide down the incline while the fluid drag will tend to cause the floc to roll or slide up the incline. When the fluid drag and the gravitational forces balance, the floc remains stationary. This balance point is approximated by determining the point at which the velocity caused by fluid drag at the centerline of the floc is the same as the opposing component of its terminal velocity along the slope.

The velocity of the fluid at the centerline of the floc can be obtained from the parabolic velocity profile in fully established laminar flow. The velocity profile can be found by solving the Navier-Stokes equations for a laminar flow (Munson 1998). The velocity profile, $v_z(r)$, is given in equation 2.

$$v_z(r) = \frac{8V_{\uparrow}}{D^2 \sin\alpha}\left(\frac{D^2}{4} - r^2\right) \tag{2}$$

where r is a coordinate normal to the tube and is set to zero at the middle of the tube. For flow in a tube the equation for the velocity gradient evaluated at the wall is:

$$\left.\frac{dv_\alpha}{dr}\right|_{r=-D/2} = \frac{8}{D \sin\alpha} V_{\uparrow} \tag{3}$$

For flow between plates separated by a distance D, the laminar flow parabolic velocity profile is described by (Munson 1998):

$$v_z(r) = \frac{6V_{\uparrow}}{D^2 \sin\alpha}\left(\frac{D^2}{4} - r^2\right) \tag{4}$$

In the following discussion a tubular geometry is assumed for purposes of discussion. However, a comparison of equations 2 and 3 shows that differences in geometry can be accounted for by a constant (i.e., a factor of 6/8 is needed to transition from tubes to plates). While other geometries such as hexagonal tubes are used in sedimentation tanks, tubes and plates represent extremes and thus, the following discussion can be generalized to other configurations.

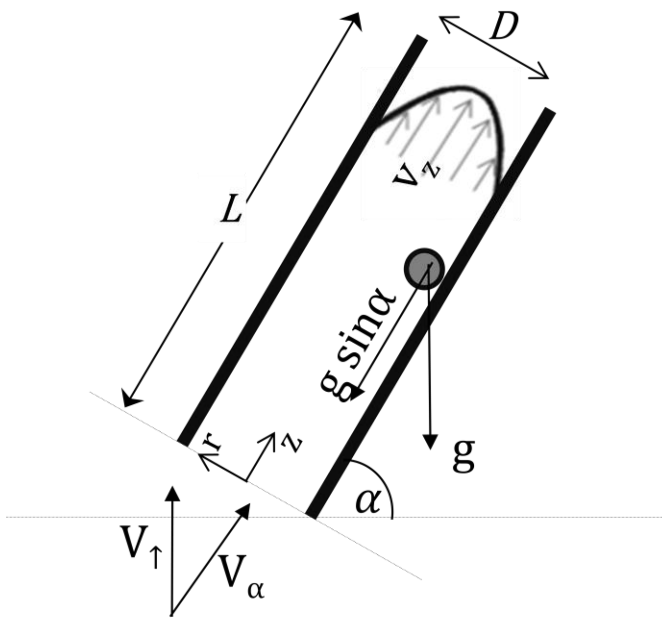

Figure 1. Definition sketch for the geometry and velocity profile experienced by a floc on the bottom surface of a tube or plate.

Inclined settlers are generally designed based on the equivalent vertical component of velocity. The relationship between the velocity in the direction of the slope and the vertical component is (see **Error! Reference source not found.**)

$$V_{\uparrow} = V_{\alpha} \sin \alpha \tag{5}$$

where $V_{\uparrow}$ is the vertical velocity component.

An approximate equation for the fluid velocity as a function of distance from the wall can be obtained by using the velocity gradient at the wall. The velocity at the center of a floc resting on the wall of a circular tube is:

$$v_\alpha\Big|_{r=\frac{D}{2}-\frac{d_{Floc}}{2}} \approx \left(\frac{4V_\alpha}{D}\right) d_{Floc} \tag{6}$$

The terminal velocity of flocs is a function of their porosity, density, and diameter. The floc density can be approximated based on a fractal model (Weber-Shirk and Lion, 2010). The diameter of a floc can be estimated from the properties of the primary colloidal particles and its terminal velocity, V_T. The terminal velocity of a floc is given by equation 7 (Adachi 1997)

$$V_T = \frac{g d_{Floc_0}}{18\Phi \upsilon_{H_2O}} \frac{\rho_{Floc_0} - \rho_{H_2O}}{\rho_{H_2O}} \left(\frac{d_{Floc}}{d_{Floc_0}}\right)^{D_{Fractal}-1} \tag{7}$$

where d_{Floc_0} is the diameter of the primary colloidal particles, d_{Floc} is the floc diameter, Φ is the floc shape factor, ν_{H_2O} is the kinematic viscosity of water, $D_{Fractal}$ is the fractal dimension, ρ_{Floc_0} is the density of the primary colloidal particle, and ρ_{H_2O} is the density of water. From this equation, the diameter of a floc can be recovered:

$$d_{Floc} = d_{Floc_0}\left(\frac{18V_T\Phi\nu_{H_2O}}{gd^2_{Floc_0}}\frac{\rho_{H_2O}}{\rho_{Floc_0}-\rho_{H_2O}}\right)^{\frac{1}{D_{Fractal}-1}} \tag{8}$$

The fractal dimension of the flocs is a critical parameter in the floc behavior. Primary particles have a fractal dimension of 3, but have a lower fractal dimension after they aggregate. Meakin determined that flocs with 2 contact points have a fractal dimension of 2.13 and flocs with 3 contact points have a fractal dimension of 2.19 (Meakin, 1988). Lambert found that the fractal dimension of *E. coli* flocs ranged from 1.90–2.20 (Lambert et al., 2003). Jarvis et al. (2005) report values of the fractal dimension ranging from 1.66 to 2.56 for coagulated natural organic matter. Nan et al. (2009) reported the fractal dimension of optimally coagulated clay suspensions to be 2.2. Li and Ganczarczyk analyzed fractal dimensions of aggregates based on reported settling tests and size-density relationships and determined a fractal dimension of 2.3 for alum aggregates (Li et al., 1989). Thus the range of the floc fractal dimension is potentially quite large and, therefore we consider a range of $D_{Fractal}$ in the calculations shown below.

The terminal velocity of a floc sliding down a frictionless surface in a quiescent fluid is obtained by using the component of gravity along the surface. The terminal velocity for laminar conditions is linearly proportional to the acceleration due to gravity. For the case of an inclined surface, the sliding velocity is proportional to the component of gravity in the direction of travel. Thus the terminal velocity down the incline of the tube settler is

$$V_{T\beta} = V_T \sin\alpha \tag{9}$$

where α is the angle between the horizontal and the tube and V_T is the terminal settling velocity in the vertical direction. Setting the fluid velocity at the floc centerline equal to the terminal velocity of the floc along the slope gives:

$$v_\alpha\Big|_{r=\frac{D}{2}-\frac{d_{Floc}}{2}} \approx V_{T\beta} \tag{10}$$

The relationship in equation 10 is an approximation of the interaction of fluid drag and the gravitation force on the floc that will cause the floc to not be able to slide down the incline. Substituting equations 5 and 9 into equation 10 results in an equation containing both the terminal velocity of a floc and the diameter of a floc.

$$V_T \sin(\alpha) \approx \left(\frac{4V_\alpha}{D}\right) d_{Floc} \tag{11}$$

Since terminal velocity and floc diameter are interdependent, it is useful to replace d_{floc} substituting equation 8 into equation.11 For design purposes the vertical velocity component is more convenient and substitution of equation 5 gives:

$$V_T \sin(\alpha) \approx \left(\frac{4V_{\uparrow}}{D\sin\alpha}\right) d_{Floc_0} \left(\frac{18 V_T \Phi \nu_{H_2O}}{g d_{Floc_0}^2} \frac{\rho_{H_2O}}{\rho_{Floc_0} - \rho_{H_2O}}\right)^{\frac{1}{D_{Fractal}-1}} \qquad (12)$$

The floc terminal sedimentation velocity in equation 12 represents the slowest settling floc that can slide down an incline. Flocs with a terminal velocity lower than V_T will be carried out the top of the tube (i.e., "roll up") even if they settle on the tube wall. Thus, this terminal velocity represents an additional constraint on the capture velocity for tube settlers. Unlike the design sedimentation capture velocity (equation 1) which is exclusively a property of the geometry and flow characteristics of the sedimentation tank, the capture velocity needed to prevent flocs from rolling up and out of the tube (referred to here as the "roll up capture velocity") is a property of the floc as well as the sedimentation tank geometry and flow characteristics. This complexity is a result of the interaction between the size of the floc and the linear velocity gradient.

The floc roll up capture velocity can be made explicit by solving equation 12 for the floc terminal velocity, V_T. Floc with this terminal velocity, which is going to be named the roll up capture velocity, $V_{cRollup}$, will be held stationary on the incline because of a balance of drag

$$V_{cRollup} \approx V_{\uparrow}\left[\left(\frac{4d_{Floc_0}}{D\sin^2\alpha}\right)^{D_{Fractal}-1}\left(\frac{18\Phi \nu_{H_2O} V_{\uparrow}}{g d_{Floc_0}^2}\frac{\rho_{H_2O}}{\rho_{Floc_0}-\rho_{H_2O}}\right)\right]^{\frac{1}{D_{Fractal}-2}} \qquad (13)$$

The floc roll up capture velocity, $V_{cRollup}$, is shown in figure 2 as a function of upflow velocity for three different tube sizes. Figure 2 illustrates that for a given upflow velocity, a decrease in tube diameter results in a higher capture velocity.

The smallest diameter tube settler that will capture a floc with a given terminal sedimentation velocity may be obtained by solving equation 13 for D:

$$D \approx \frac{4}{\sin^2 \alpha} \frac{V_{\uparrow}}{V_t} d_{Floc_0} \left(\frac{18 V_T \Phi \nu_{H_2O}}{g d_{Floc_0}^2} \frac{\rho_{H_2O}}{\rho_{Floc_0} - \rho_{H_2O}} \right)^{\frac{1}{D_{Fractal} - 1}} \tag{14}$$

Equation 14 provides a method to calculate a minimum tube diameter given a target floc terminal velocity to be captured. The following figures summarize the model's theoretical predictions.

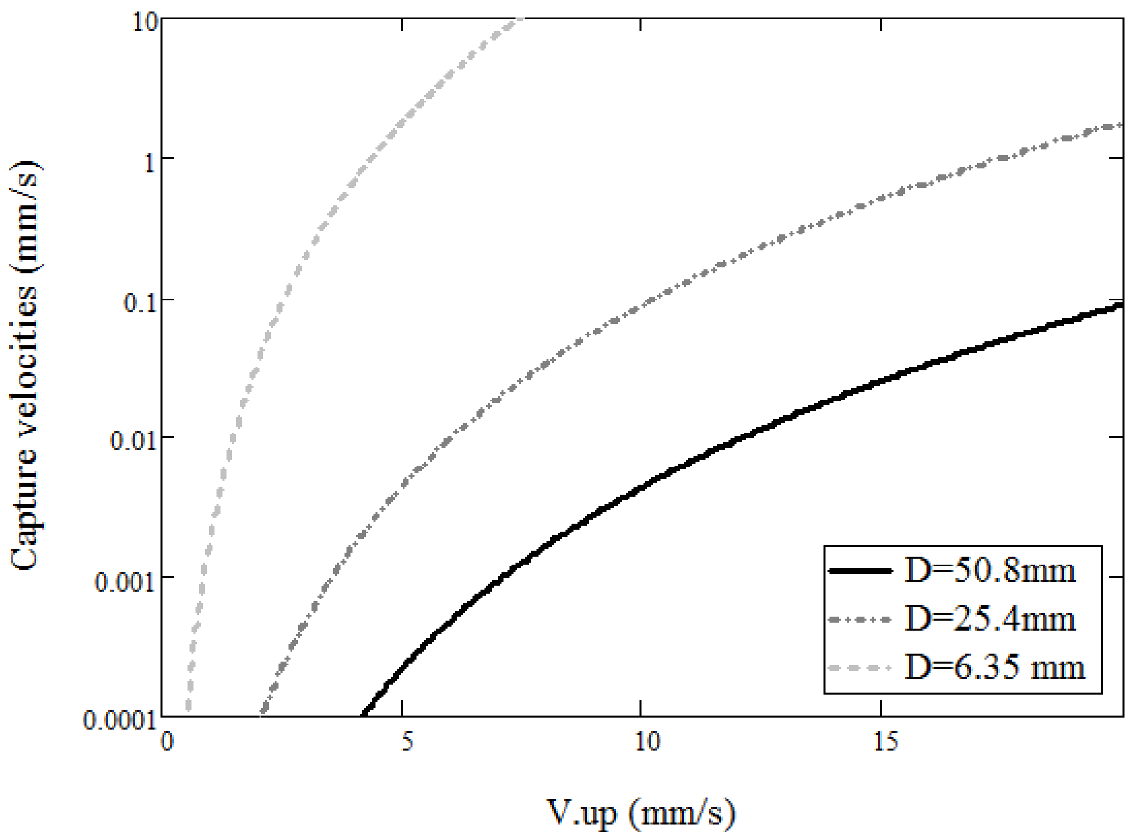

Figure 2. Theoretical tube settler capture velocities ($V_{cRollup}$) for 3 different inner tube diameters (D). Capture velocities are the minimum terminal settling velocities of flocs that will be retained on an inclined surface because of a balance between gravity forces and fluid drag. The floc parameters assumed for calculation were: $D_{Fractal}$ =2.3, d_{Floc_0} = 1 μm, and ρ_{Floc_0} = 2624 kg/m^3. Essentially, this figure indicates that larger tube diameters are required to achieve good performance at higher up flow velocities. It is also predicted that larger diameter tubes can have an average velocity greater than Willis' recommended 1.70 mm/s and still achieve 0.1 mm/s capture velocity.

Caveats: Fractal dimension, Primary Particle Size, Entrance Region

It is important to keep in mind the underlying assumptions made for the model presented above, because theoretically, slight changes to these assumptions such as the fractal dimension and primary particle size could yield different results. The fractal dimension assumed for the model was 2.3. If the floc fractal dimension is only slightly greater than 2, the exponent of the right hand side in equation 13 can be quite large. The exponent on the up flow velocity, $V_{\uparrow}$, is $\frac{D_{Fractal}-1}{D_{Fractal}-2}$. For a fractal dimension of 2.3 the exponent has a value of 4.3 and for a fractal dimension of 2.2 it increases to 6. It is predicted that flocs with a fractal dimension slightly above 2.0 are especially vulnerable to rolling up the tube settlers. Flocs with fractal dimensions greater than 2 become less susceptible to floc roll up as they increase in size and thus floc aggregation on the slope aids in transport to the bottom of the tube. It is also predicted that floc roll up is independent of tube size for a floc fractal dimension of 2. Assuming a fractal dimension of 2.3, the influence of primary particle size on floc roll up potential is illustrated in Figure 2. Kaolin clay was used as the turbidity source for the experiments; however, natural streams have heterogeneous water composition that may provide range of sizes for floc primary particles.

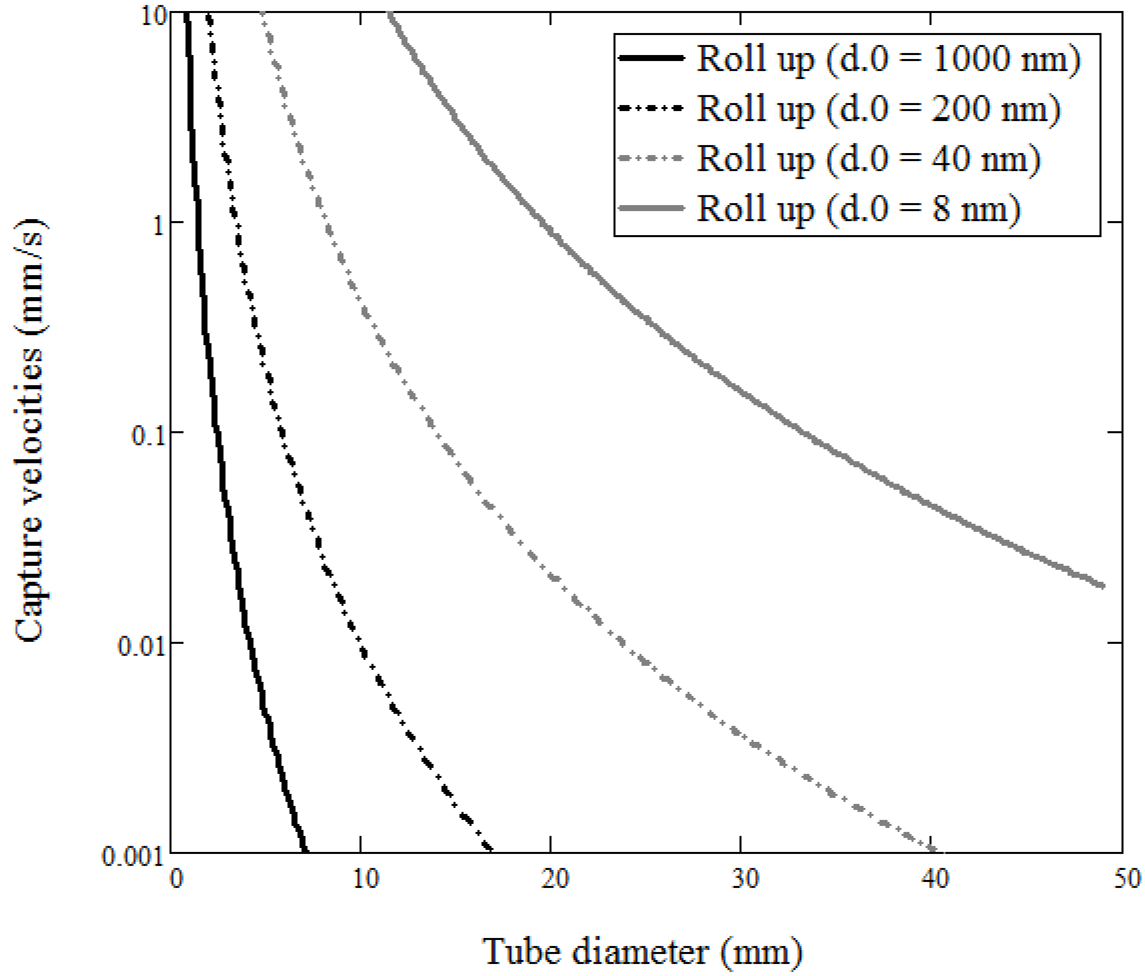

Figure 2. Theoretical roll up capture velocities for tube settlers given 4 different primary particle sizes. The calculations assume: $V_{\uparrow}$ = 1 mm/s, $D_{Fractal}$ =2.3, ρ_{Floc_0} = 2624 kg/m^3. It is predicted that flocs with smaller primary particles will require larger diameter tube settlers. Flocs with smaller primary particles are more susceptible to shear and on average will form smaller stable floc particles with lower settling velocities.

Furthermore, the roll up capture velocity described above is defined based on a fully developed laminar flow velocity profile. At the entrance region to a tube or at the edge of a lamellar plate boundary effects are extant and can extend into the core of the flow at a distance L_e given by equation 15 (Munson 1998).

$$L_e = 0.06D\,Re \tag{15}$$

Where Re is the Reynolds number and is given in equation 16.

$$Re = \frac{V_\alpha D}{\upsilon_{H_2O}} \tag{16}$$

At the entrance region, the flow profile is not fully developed. This means that it is important to consider the fate of flocs that are able to slide down from the region of fully developed flow into the entrance region. As the velocity gradient at the wall increases, some flocs sliding down from above will be unable to continue down the slope. As more flocs slide down from above the trapped flocs will grow and, as they grow, they become able to progress further down toward the entrance region. The entrance to the tube presents a zone with very high velocity gradients and experimental observations reveal the formation of a large rotating mass of flocs at the entrance to tubes that maintains a pseudo steady state volume by releasing flocs in bursts back into the sedimentation tank. For small diameter tube settlers, this formation occupies a significant portion of the tube, and its effects on performance are not yet known.

Materials and Methods

Raw Water

Conditions of constant input were created using a concentrated kaolin clay suspension diluted with temperature controlled, aerated tap water to produce a raw water source for treatment. Cornell University tap water was used for all experiments (pH ≈ 7.5 ± 0.3 pH units; total hardness (150mg 1^{-1} as $CaCO_{3(s)}$), total alkalinity (111 mg l^{-1} as $CaCO_{3(s)}$) and total organic carbon (2.0 mg l^{-1}) (City of Ithaca 2010).

Water temperature was kept at 21ºC with a coefficient of variation of ±1% and was sampled utilizing a thermistor. When the temperature varied above or below 21ºC, a solenoid valve was opened inflowing cold or hot water, respectively. The temperature controlled water was aerated to reduce the concentration of supersaturated gases.

Kaolin clay was utilized to provide a controlled level of turbidity. The raw water turbidity was continuously sampled by a turbiditymeter coupled with a feed-back control loop. The process was automated by a process controller created using LabView. The raw water turbidity was 100 NTU with a coefficient of variation of ±5%.

Coagulant Dosing

A laboratory grade alum solution was prepared daily with distilled water. The alum dosage of 45 mg/L (4.23 mg/L Al), was utilized and produced a majority of particles with settling velocities greater than the 0.12 mm/s design capture velocity used by Hurst et al (2010). A raw water flow of 712.6 mL/min was used in all experiments. Raw water and alum were rapidly mixed by flowing through a tube 4.8 mm ID (inner diameter), 1 m in length with an energy dissipation rate of 0.1 W/kg.

Tube Flocculator

A tubular flocculator was used to prior to sedimentation to facilitate particle aggregation. The flocculator had a length (L) of 26 m, a coil diameter of 13.5 cm, an inner diameter (D) of 0.95 cm, a head loss (h_L) of 0.159 m, and had a hydraulic residence time (θ) of 156 sec. The Reynolds number for the tube flocculator was 1590 ensuring laminar flow. For laminar flow the collision potential of a flocculator is proportional to $G\theta\phi_{Floc_0}^{\frac{2}{3}}$ (Adachi 1997) where $G\theta$ is given in equation 17:

$$G\theta = D\sqrt{\frac{\pi}{4}\frac{gh_L}{\nu_{H_2O}}\frac{L}{Q}} \quad (17)$$

and ϕ_{Floc_0} is the floc volume fraction, which in turn is proportional to the concentration of Clay and Alum present in the system. In this case, ϕ_{Floc_0} was equal to 4.257 10^{-5}. Equation 17 can be derived by substituting the relationship for the energy dissipation rate (ε) given by equation 18

$$\varepsilon = \frac{gh_L}{\theta} \quad (18)$$

into the equation 19 below for the velocity gradient (G) in the flocculator:

$$G = \sqrt{\frac{\varepsilon}{\nu_{H_2O}}} \quad (19)$$

The average energy dissipation rate in the flocculator used was about 10 mW/kg. Equation 19 can then be combined with equation 20 below, which describes the hydraulic residence:

$$\theta = \frac{L}{Q}\frac{\pi D^2}{4} \quad (20)$$

where Q is the volumetric flow rate.

The $G\theta$ for the tube flocculator was 260. Although this value is on the low end of that commonly used for hydraulic flocculators, it performed well in this study because the floc volume fraction was relatively high (given 100 NTU source water).

Floc Blanket

In a manner comparable to the experimental system described by Hurst et al., the sedimentation tank utilized upflow in the presence of a floc blanket. The sedimentation tank upflow velocity was 1.2 mm/s and was set to be close to the optimal up flow velocity for turbidity removal determined by Hurst et al. (2010). All experiments presented in this paper were run with a floc blanket, and results may be vastly different for clarifiers without floc blankets. The floc blanket not only provides an added clarification process but also creates a more uniform particle size distribution for flocs entering the lamellar system.

Process Control

Process Control software guides the experiment process. Clay is added until 100 NTU influent turbidity is achieved. Once achieved, the the raw water turbidity is combined with the alum solution and flows into the coiled tube flocculator. After the flocculator, the water flows into a sedimentation column and forms a floc blanket. After a floc blanket reaches the height of the floc weir (), the effluent turbidity in the tube settler is sampled. For small experimental flow rates, a reservoir is used to accumulate and then sample effluent turbidity. Turbidity data is acquired and recorded every 5 seconds from the turbidimeters.

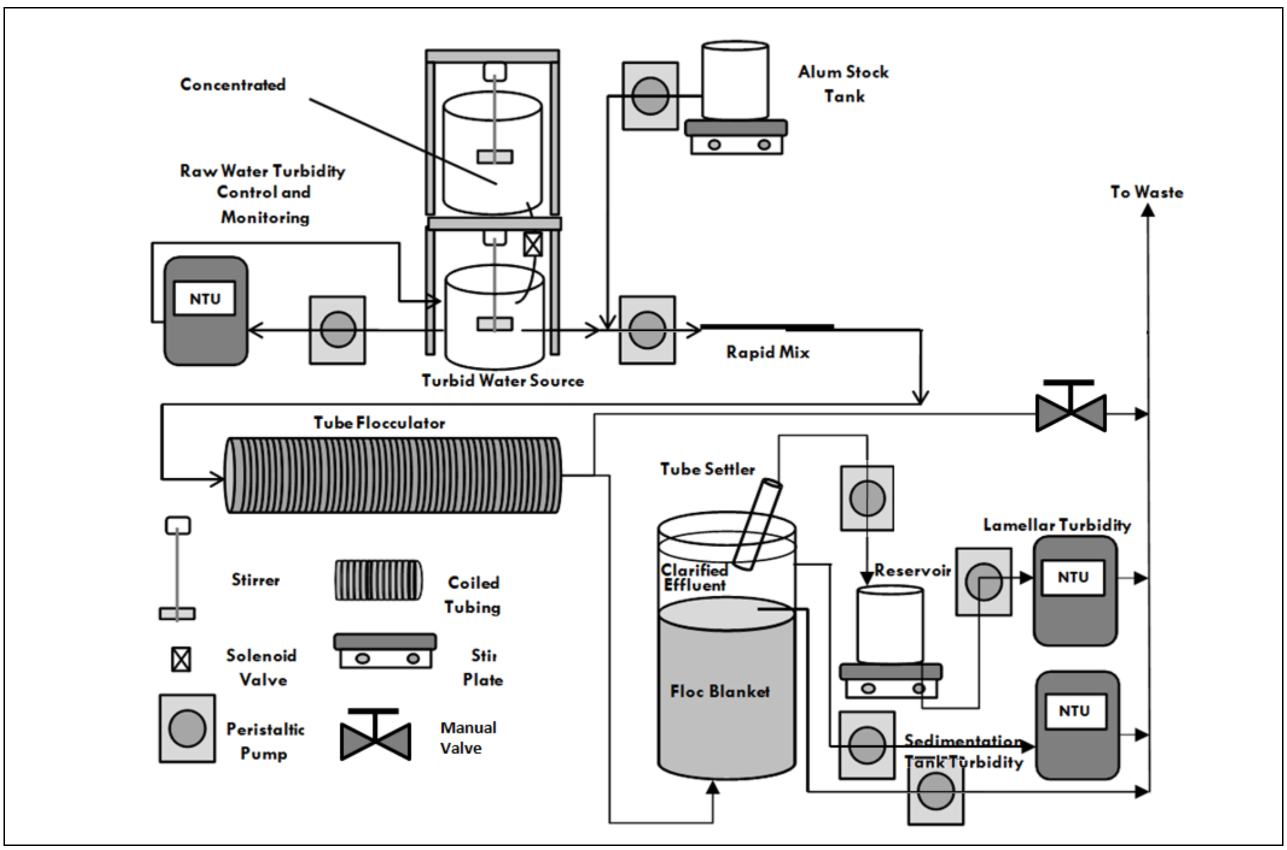

Figure 3. Schematic of laboratory set-up and turbidity monitoring.

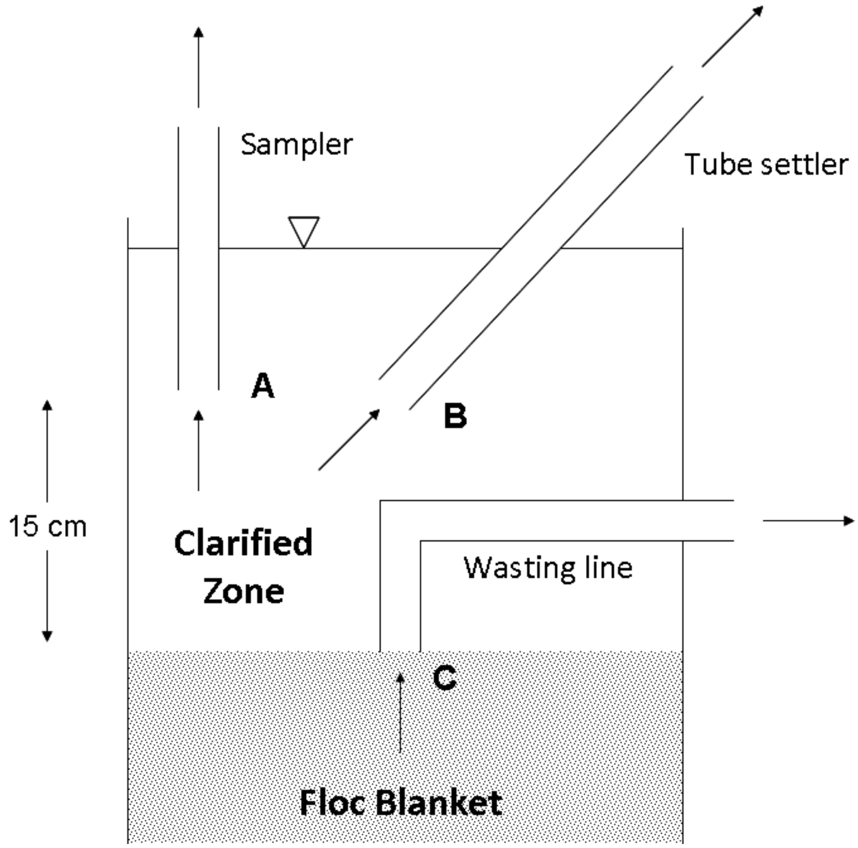

Figure 4. A Schematic of the influent sample point and tube settler inlet in the top portion of the clarifier column. Water is sampled at A to measure the influent turbidity to the tube settler, and is pumped through the sampler at a velocity equivalent to the reactor upflow velocity (V_{Up}) to prevent settling. Water enters the tube settler at B, and the performance of the tube settler is quantified by turbidity measurement subsequent to particle removal by the tube. Floc is wasted from the floc blanket at C, which controls the elevation of the floc blanket.

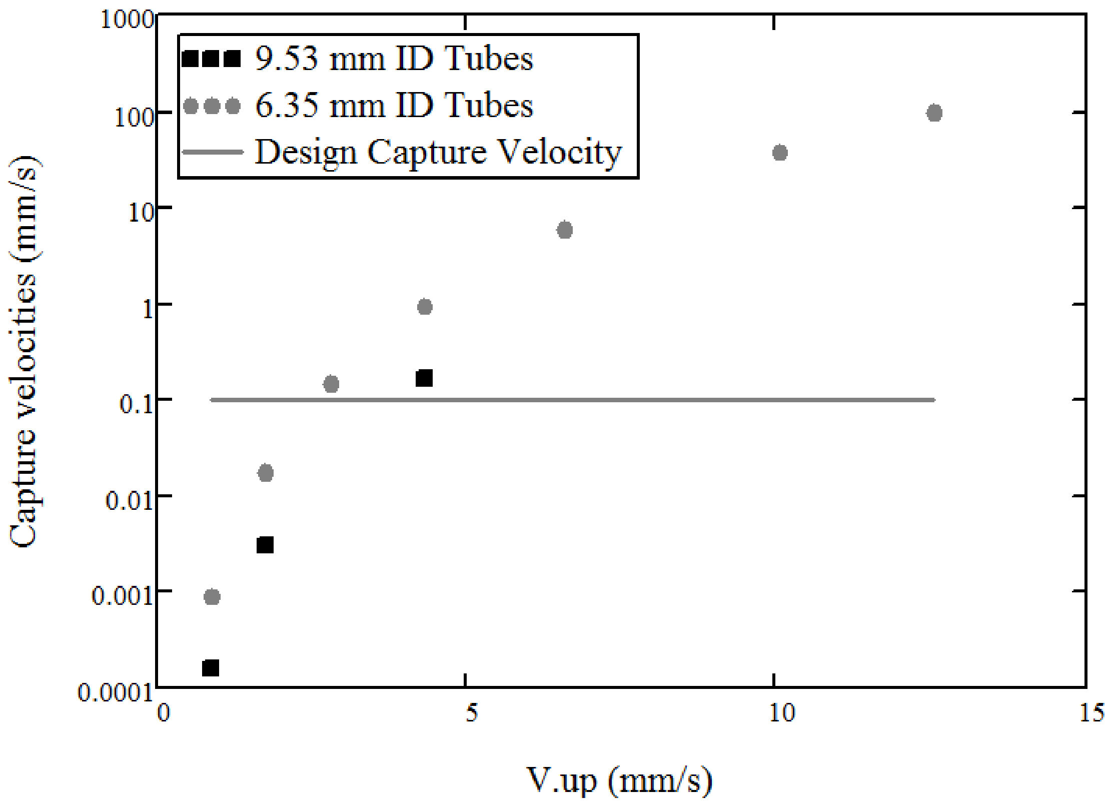

Figure 7. Predicted roll up capture velocities for the two tube diameters (6.35 mm and 9.53 mm) used in the experiments. The upflow velocities and tube lengths were varied for each diameter to maintain the same sedimentation design capture velocity for all experiments. The parameters were ($V_{\uparrow}$ = 1 mm/s, $D_{Fractal}$ = 2.3, ρ_{Floc_0} = 2624 kg/m^3). It is therefore expected that all flocs with a settling velocity lower than each point are going to contribute to the effluent turbidity.

Data Acquisition and Sampling

Continuous effluent turbidity readings of the floc blanket clarified effluent (i.e. the suspension within the sedimentation tank above the floc blanket) and the tube settler effluent were taken using Micro TOL Turbidimeters (HF Scientific Model 20053, Ft. Myers, Forida). A schematic of the apparatus showing sampling points is given in Figure 6. Particle removal is reported below in terms of negative log fraction remaining (pC*).

$$pC^* = -\log\left(\frac{C_{Effluent}}{C_{Influent}}\right) \qquad (21)$$

pC* is a convenient dimensionless measure of particle removal efficiency that is independent of the influent turbidity. In this study, pC* was calculated for overall removal efficiency of the floc blanket and tube settler ($pC^*_{Overall}$), for the floc blanket ($pC^*_{Floc\,Blanket}$), and for the tube settler ($pC^*_{TubeSettler}$). By definition $pC^*_{Overall}$ is the sum of $pC^*_{TubeSettler}$ and $pC^*_{Floc\,Blanket}$.

Table 1. Summary of system parameters and model assumptions

Raw Water Temperature:	21ºC ±1%
Raw Water Flow Rate:	712.6 mL/min
Raw Water pH:	7.5 ± 0.3 pH units
Total Hardness:	150mg 1^{-1} as $CaCO_{3(s)}$
Influent Turbidity:	100 NTU ±5%
Alum Dosage:	45 mg/L Al
Rapid Mix Inner Diameter:	4.8 mm
Rapid Mix Length:	1 m
Rapid Mix Energy Dissipation Rate:	0.1 W/kg
Flocculator Length (L):	26 m
Flocculator Coil Diameter:	13.5 cm
Flocculator Inner Diameter (D):	0.95 cm
Flocculator Head Loss (h_L)	0.159 m
Flocculator Residence Time (θ):	156 sec
Flocculator Energy Dissipation Rate (ε):	10 mw/kg
G-theta ($G\theta$):	260
Floc Volume Fraction (ϕ_{Floc_0}):	4.257 10^{-5}
Sedimentation Upflow Velocity:	1.2 mm/s
Assumed Fractal Dimension ($D_{Fractal}$):	2.3
Floc Density (ρ_{floc}):	2624 kg/m^3

Table 2. Summary of tube geometries and flow rates

Tube diameter (mm)	Length (m)	Flow rate (mL/min)

6.35	0.12	1.90
6.35	0.24	3.79
6.35	0.40	6.18
6.35	0.62	9.49
6.35	0.65	14.44
6.35	1.15	17.37
6.35	1.20	18.18
6.35	1.83	27.53
9.53	0.36	8.54
9.53	0.93	21.34

Experimental Results

Constant 0.10 mm/s design capture velocity experiments have been conducted using tube settlers of two different inner diameters, 6.35 mm and 9.53 mm respectively, for a range of V_α. Figure 11 gives the measured pC*s as a function of V_α. When V_α increases, the performance of the system decreases, while the performance of the floc blanket remains relatively consistent with the increasing V_α for an average value of pC* of 1.12. The graph shows a first order decreasing trend of the system performance.

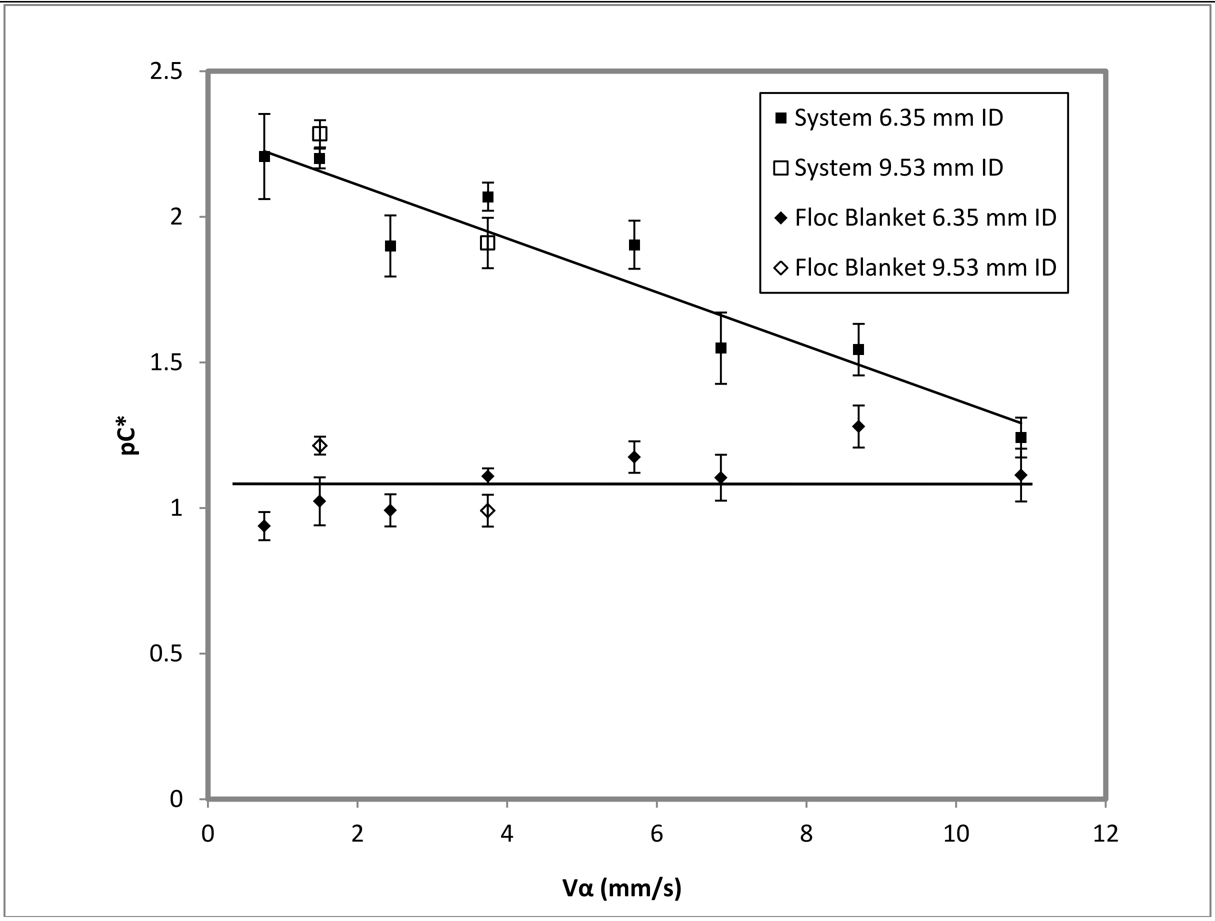

Figure 5. This graph shows that the floc blanket pC* remained very constant over the whole range of experiments except for one point.

Figure 12 shows the tube settler pC* as a function of V_α. When V_α increases, the performance of the tube settler decreases, and the fluctuations in performance become large. The graph shows a first order decreasing trend of the tube settler performance.

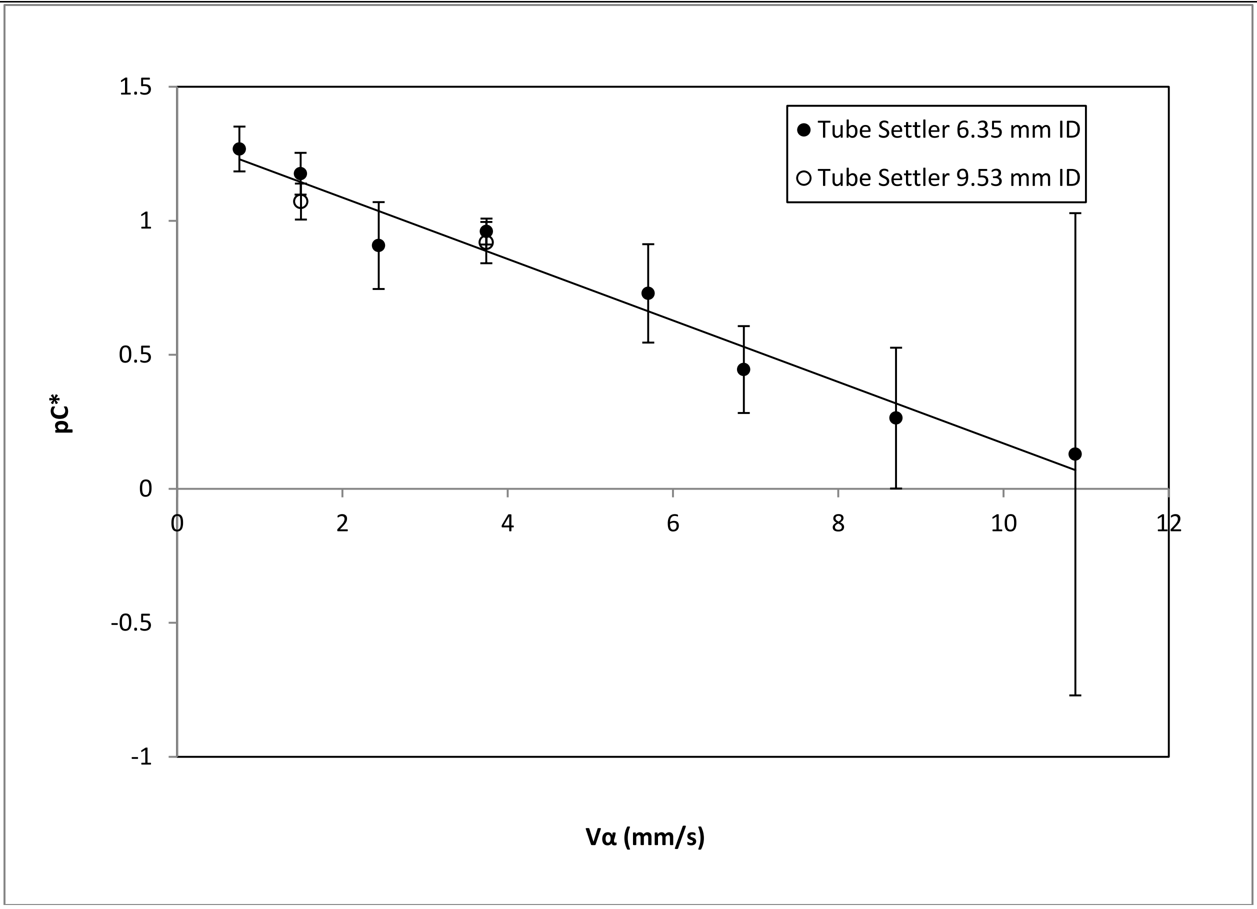

Figure 6. This graph shows that the tube settler pC* decreases and becomes more unstable as the velocity gradient increases.

Discussion

All the above results are given for tubes. $V_{cRollup}$ is dependent on the velocity gradient, which is ¾ less for plates than for tubes. All equations with the linearized velocity gradient at the wall are therefore changed by a factor of ¾ for plates. Thus for a given $V_{\uparrow}$, $V_{cRollup}$ for plates will be smaller than the $V_{cRollup}$ for tubes. Thus plates are slightly less vulnerable to floc roll up than are tubes given the same diameter and spacing.

Conclusions

The floc roll up model delineates a failure mechanism that prevents flocs from sliding along an inclined surface in the countercurrent direction. This failure is caused by fluid drag resulting from velocity gradients at the plate or tube wall that oppose gravity forces. Velocity gradients increase as the plate settler spacing or tube diameter is decreased and as the upflow velocity is increased. We expect that high velocity gradients will cause flocs to "roll up" an inclined surface and act to increase effluent turbidity. If the tube settler diameter or plate settler spacing is too small, high velocity gradients can cause roll-up of flocs that would otherwise be captured.

Evaluated this phenomenon utilizing a combined tube-settler floc blanket system to characterize the removal effectiveness for colloidal particles at different flow conditions, but at a constant design capture velocity of 0.1 mm s^{-1}. Experimental data suggests that plate spacing as small as 1 cm for an upflow velocity of 1 mm/s can be implemented without causing performance deterioration.

Tube settler performance deteriorated when the the floc roll up capture velocity was larger than the sedimentation design capture velocity.

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References

Adachi, Y. and Tanaka, Y. (1997) Settling velocity of an aluminum-kaolinite floc. Water Res. 31(3), 449-454.

Bache, D.H. and Gregory R. (2007) Flocs in Water Treatment (2007), IWA Publishing, London

Gmachowski, L. (2006) Scale-invariant growth of fractal aggregates. Colloids Surf. Physicochem. Eng. Aspects 274(1-3), 223-228.

Hurst, M.W., Weber-Shirk, M.; and Lion, LW. (2010) Parameters Affecting Steady-state Floc Blanket Performance; Aqua, 59(5), 312-323.

Jarvis, P., Jefferson, B., and Parsons, S. A. (2005), Breakage, regrowth, and fractal nature of natural organic matter flocs, Environ. Sci. Technol. 39, 2307-2314.

Lambert, S., Moustier, S., Dussouillez, P., Barakat, M., Bottero, J. Y., Le Petit, J., Ginestet, P. (2003) Analysis of the structure of very large bacterial aggregates by small-angle multiple light scattering and confocal image analysis. J. Colloid Interface Sci. 262(2), 384-390.

Letterman, R. D. and Iyer, D. R. (1985) Modeling the effects of hydrolyzed aluminum and solution chemistry on flocculation kinetics. Environmental Science and Technology 19(8), 673-681.

Li, D. and Ganczarczyk, J. (1989) Fractal geometry of particle aggregates generated in water and wastewater treatment processes. Environmental Science and Technology 23(11), 1385-1389.

Long, S. and Kress, K. L. (2009) Floc Blanket Formation. Accessed 9/7 2009. https://confluence.cornell.edu/display/AGUACLARA/PSS+Floc+Blanket+Formation

Meakin, P. (1988) FRACTAL AGGREGATES. Adv. Colloid Interface Sci. 28(4), 249-331.

Munson, B., Young, D., Okiishi, T. (1998) Fundamentals of Fluid Mechanics. Third Edition. John Wiley & Sons.

Nan, J., He, W., Song, J., Xinxin Song, X. (2009) Fractal Growth Characteristics of Flocs in Flocculation Process in Water Treatment. *Proceedings of the 2009 International Conference on Energy and Environment Technology (ICEET 2009)*, p 582-8, 2009.

Tambo, N. and Watanabe, Y. (1979) Physical characteristics of flocs. I. the floc density function and aluminium floc. Water Res. 13(5), 409-19.

Wu, R. M. and Lee, D. J. (1998) Hydrodynamic drag force exerted on a moving floc and its implication to free-settling tests. Water Research 32(3), 760-768.