Floc Roll-up and its Implications for the Spacing of Inclined Settling Devices

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Key words: sedimentation, inclined sedimentation, plate settler, tube settler, capture velocity, floc roll-up, velocity gradient, fractal dimension

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Abstract

Inclined plate and tube settlers are commonly used to make sedimentation tanks more compact. Conventional design equations for inclined settling devices are based on obtaining a desired particle capture velocity, and these equations suggest that a suitable capture velocity can be achieved by reducing plate settler spacing or tube settler diameter below that specified in conventional design guidelines. Smaller spacing would reduce capital cost by decreasing sedimentation tank volume. However, the existing literature does not explain why smaller values of plate or tube spacing cannot be used, and the failure mechanism that sets the minimum spacing recommended in design practice has not been documented. This research shows that the fluid velocity gradient at the tube or plate surface is the limiting constraint for spacing, and for very small spacing, particles that settle on the solid surface are carried up the incline. This failure mode, termed "floc roll-up," occurs when the terminal velocity of a floc along the incline is less than the upward velocity of the fluid at the center of the floc. This paper presents an experimental and theoretical investigation of the floc roll-up failure mode and its implications for plate settler design. A model is developed to explain the physics of floc roll-up, and experiments in a bench-scale water treatment apparatus demonstrate its effects on sedimentation performance.

Key words: sedimentation, inclined sedimentation, plate settler, tube settler, capture velocity, floc roll-up, velocity gradient, fractal dimension

INTRODUCTION

Inclined plates or tubes are often employed to reduce the required area of new sedimentation tanks or to retrofit existing tanks and increase their capacity (Reynolds and Richards, 1996). Inclined settling devices are widely used in water and wastewater treatment, and as such, there is a large existing body of research on the optimal configurations for these systems. Reducing the spacing of inclined settling devices would decrease the cost of conventional municipal-scale treatment facilities by allowing for shallower sedimentation tanks. The possible benefit of reduced spacing is particularly important when considering both the large requirement for water infrastructure upgrades across the industrialized world, and the need for affordable water treatment technologies to expand access to safe drinking water in the developing world. Unfortunately, the spacing of the inclined plates or tubes is one design parameter that has not been extensively studied.

Existing documentation reveals suggested spacing ranging over more than an order of magnitude - from 1.3 to 30 cm - based on empirical evidence (AWWA, 1999; Hansen and Culp, 1967). However, little to no theoretical basis exists for these guidelines, and the technical literature provides no exploration of how local flow conditions between the inclined plate or tube surfaces affect particle capture. An American Water Works Association design book recommends a spacing of 30 cm for vertical-flow sedimentation tanks with floc blankets and asserts that widely spaced plate settlers are more cost-effective in floc blanket clarifiers (AWWA, 1999); however, no detailed analysis is presented. In contrast, Ziolo (1996) recommends a 5 cm spacing for "ordinary" performance in general sedimentation applications and suggests that spacing could be adjusted based on the influent solids concentration. Experiments by Hansen and Culp (1967) showed that circular tube settlers could achieve up to a 96% reduction in turbidity with a spacing of 1.3 cm, a significantly smaller value than the 5 cm suggested by Ziolo.

In addition to the suggested spacing of inclined settling devices, existing literature also disagrees on the physical basis upon which this spacing should be determined. Some researchers have characterized inclined sedimentation performance in terms of the ratio of plate length, L, to center-to-center spacing D, where improved performance was correlated with higher L/D ratios. For example, Yao (1970) reports that good performance was achievable for L/D ratios between 20 and 40. Beyond a ratio of 40, increasing the length of the plates or tubes yielded diminishing returns in terms of particle removal performance. Willis (1978) indicates that the greatest concern for small plate spacing is the danger of high velocities sweeping settling sludge out with finished water. Willis addresses this concern by designating the maximum tube loading rate as 1.7 mm/s and states that this tube settler design velocity "has proven reasonably satisfactory" in field applications.

In the research presented here, laboratory studies and model calculations are used to explore the quantitative relationship between flow conditions, geometry, and performance of inclined settling devices. A failure mode termed "floc roll-up" is proposed as the fundamental physical constraint on reduced spacing in inclined sedimentation systems. The theoretical effects of floc roll-up are explored and presented alongside experimental studies with a controlled bench-scale system.

THEORETICAL MODEL DEVELOPMENT

Capture velocity and the floc roll-up condition

Successful capture of a floc by an inclined settling device requires three steps. First, the floc must be able to settle onto the surface of a plate or tube settler; second, it must slide down the incline to reach the lower section of the sedimentation tank; and third, the floc must be removed from the lower section of the sedimentation tank. The settle step is well characterized and is based on the geometry and flow through the inclined settlers. The second step, or slide step, is the focus of this paper.

A schematic of an inclined sedimentation device is shown in Figure 1. For such a device - i.e., a tube settler with ends perpendicular to the axis - the settle capture velocity (referred to as critical velocity in some of the previous literature) is given by Equation (1) (Schulz and Okun, 1984):

$$V_{Settle} = \frac{V_\alpha}{\frac{L}{D}\cos\alpha + \sin\alpha} \tag{1}$$

where L is the length of the tube settler, D is the tube diameter, α is the angle of inclination, V_α is the average fluid velocity in the tubes, and V_{Settle} is the terminal velocity of the slowest-settling particle that is reliably captured. Equation (1) suggests that tube settler performance (as manifest by V_{Settle}) is maintained as long as the ratio of L/D is constant for a fixed V_α. Thus, according to this theory, it should be possible to reduce the required length of the tube settlers by decreasing their diameter, and it is not clear in Equation (1) why the value of D should not simply be made as small as possible.

"Floc roll-up" is presented here as a failure mode that places a lower limit on the allowable diameter of tube settlers or the allowable spacing of plate settlers. After a floc settles on the lower surface of an inclined settling device, it continues to experience an upward drag caused by the fluid flow, and the velocity at the centerline of the floc increases if the spacing between the plates or the diameter of the tubes is decreased. This is the case even if a constant average fluid velocity is maintained, because the velocity gradient at the wall increases as the spacing decreases. The gravitational force acts in the direction of down the incline, while fluid drag acts in the direction of up the incline. When the fluid drag and gravitational forces balance, the floc remains stationary. This force balance sets the minimum required spacing for plate or tube settlers. The force balance can also be obtained equating the velocity caused by fluid drag at the center line of the floc to the floc's terminal settling velocity (in the absence of fluid flow) along the slope.

Fluid velocity at the floc centerline

The velocity of the fluid at the centerline of a floc can be obtained from the parabolic velocity profile in fully-established laminar flow. This velocity profile $v_z\{r\}$ can be found by solving the Navier-Stokes equations for laminar conditions (Munson et al., 1999), as shown in Equation (2):

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

where r is a coordinate normal to the tube axis and is set to zero at the middle of the circular tube. The equation for the velocity gradient evaluated at the tube wall is:

$$\frac{dv_\alpha}{dr}\mid_{D/2} = \frac{8V_\alpha}{D} \tag{3}$$

For flow between plates separated by a distance D, the laminar flow parabolic velocity profile is described by Equation (4) (Munson et al., 1999):

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

In the following discussion a tubular geometry is assumed. However, a comparison of Equations (2) and (4) shows that differences in geometry can be accounted for by a constant - i.e., a factor of 6/8 is needed to convert from tubes to plates. While other geometries such as hexagonal tubes are also used in inclined settling devices, tubes and plates represent extremes and the following discussion can therefore be generalized to other configurations.

Inclined settlers are typically designed based on the vertical component of fluid velocity. The relationship between the velocity in the direction of flow (i.e. along the incline) and the vertical component is:

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

where $V_\uparrow$ is the average velocity in the vertical direction. An approximate equation for the fluid velocity near the tube wall and parallel to the incline as a function of distance from the wall can be obtained by linearizing the velocity gradient at the wall of the tube, using the derivative in Equation (3). This, in turn, allows for the velocity v_α experienced at the center of a floc of diameter d_{Floc} resting on the wall of a circular tube to be approximated by:

$$v_\alpha \left\{ \frac{D}{2} - \frac{d_{Floc}}{2} \right\} \approx \frac{8V_\alpha}{D} \left(\frac{d_{Floc}}{2} \right) = \frac{4V_\alpha d_{Floc}}{D} \tag{6}$$

Note that this is a valid approximation when the floc diameter d_{Floc} is very small compared to the diameter D of the tube settler.

Floc terminal settling velocity along the inclined surface

The terminal velocity of flocs sliding down the surface of an incline in the absence of fluid flow depends on their porosity, density, and diameter. Floc density can be approximated based on a fractal model (Weber-Shirk and Lion, 2010). Adachi and Tanaka (1997) model the terminal velocity V_T of a vertically-settling floc using Equation (7):

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

where d_{Floc_0} is the diameter of the primary colloidal particles, d_{Floc} is the floc diameter, Φ is a floc shape factor, ν_{Water} 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_{Water} is the density of water. For clay-aluminum flocs, Tambo and Watanabe (1979) report a drag coefficient equal to $45/Re$, where Re is the Reynolds number. Because the drag coefficient for spheres is equal to $24/Re$ for laminar conditions, the value of the floc shape factor Φ is taken to be $45/24$.

The fractal dimension is a critical parameter in describing floc behavior. Meakin (1987) determined that flocs with two contact points have a fractal dimension of 2.13 and flocs with three contact points have a fractal dimension of 2.19. Lambert et al. (2003) found that the fractal dimension of *E. coli* flocs ranged from 1.90 to 2.20. 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) indicate that the fractal dimension of optimally-coagulated clay suspensions is 2.2. Li and Ganczarczyk (1989) analyzed the fractal dimensions of aggregates based on settling test data and size-density relationships and determined an average fractal dimension of 2.3 for alum aggregates. The range of the floc fractal dimension is potentially quite large.

The terminal settling velocity of a floc sliding down a frictionless inclined surface in a quiescent fluid is obtained by using the component of gravitational force along the incline. The terminal velocity for laminar conditions is linearly proportional to the acceleration due to gravity. The terminal velocity $V_{T\alpha}$ down the incline of the tube settler is therefore:

$$V_{T\alpha} = V_T \sin\alpha \tag{8}$$

where α is the angle between the horizontal and the inclined tube and V_T is the terminal settling velocity in the vertical direction.

Floc roll-up predictions

Setting the fluid velocity at the floc centerline equal to the terminal sliding velocity of the floc along the slope gives the critical condition for floc roll-up, as shown in Equation (9):

$$v_\alpha \left\{ \frac{D}{2} - \frac{d_{Floc}}{2} \right\} = V_{T\alpha} \tag{9}$$

The relationship in Equation (9) is an approximation of the interaction of fluid drag and the gravitational force on the floc that will cause the floc to remain stationary on the incline. Substituting Equations (6), (7), and (8) into Equation (9) and solving for the terminal velocity V_T that will balance the velocity up the incline at the center of the floc yields a general floc roll-up model:

$$V_{Slide} \approx V_{\uparrow} \left(\frac{4d_{Floc_0}}{D \sin^2 \alpha} \right)^{\frac{D_{Fractal}-1}{D_{Fractal}-2}} \left[\frac{18 V_{\uparrow} \Phi \rho_{Water} \nu_{Water}}{g d^2_{Floc_0} \left(\rho_{Floc_0} - \rho_{Water} \right)} \right]^{\frac{1}{D_{Fractal}-2}} \tag{10}$$

The sedimentation velocity V_{Slide} in Equation (10) is the terminal sedimentation velocity of the slowest-settling floc that can slide down the wall of an inclined settling device under the given conditions. Flocs with this terminal velocity (the slide velocity) will be held stationary on the incline because of a balance between gravitational forces and fluid drag. Flocs with a terminal velocity lower than V_{Slide} will be carried out the top of the tube (i.e., "roll up") even if they settle onto the tube wall. Thus, the slide terminal velocity represents a constraint on the ability of tube settlers to capture flocs. Unlike the settle capture velocity in Equation (1), which is exclusively a property of the geometry and flow characteristics of the sedimentation tank, the slide 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, its density, and the velocity gradient in the fluid.

The slide capture velocity V_{Slide} is plotted in Figure 2 as a function of upflow velocity for inclined tube settlers ($\alpha = 60^o$) of three different diameters, using the model in Equation (10) and assuming typical properties of clay-aluminum hydroxide flocs. Typical settle capture velocities ranging from 0.24 to 0.47 mm/s for flocculated water (Reynolds and Richards, 1996) are indicated in the shaded region of the figure. Inclined settling devices are designed to achieve a certain settle capture velocity, and floc roll-up will become a problem when V_{Slide} from Equation (10) is greater than this settle capture velocity. The floc roll-up failure mode provides a rationale for limiting the spacing or velocity in inclined settling devices. However, Figure 2 indicates that even small diameter tubes can have an average vertical fluid velocity greater than the 1.70 mm/s recommended by Hansen and Culp (1967) and still achieve a good settle capture velocity.

Model limitations

The model results presented above are strongly dependent on the assumed floc properties, and the fractal flocculation model indicates that floc properties are dependent on the density and size of the primary particle as well as the floc fractal dimension. Water treatment plants must successfully remove a wide range of particles including clay, organic matter, and coagulant. It is necessary to consider the worst-case scenario for floc roll-up, and further research will be required to determine the properties of the flocs that are most difficult to capture. Flocs formed from organic matter are expected to be less dense and thus more susceptible to floc roll-up.

The slide capture velocity described above is defined based on a velocity profile for fully-developed laminar flow. The length of the entrance region is a function of the Reynolds number. The slide velocity model presented above assumes that the plate or tube settler is sufficiently long to achieve fully-developed flow. In the entrance region of a tube or plate, the velocity gradient at the wall is higher than in the fully-developed region. This means that it is also 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 accumulate and eventually become able to progress further down toward the entrance region in a small avalanche. This avalanche behavior is not part of the model, but it does not seem to present a constraint on the capture of flocs.

MATERIALS AND METHODS

Raw water preparation

Influent water of approximately constant characteristics was prepared for the bench-scale experiments using temperature-controlled, aerated tap water dosed with concentrated kaolin clay. A schematic of the apparatus used to condition the raw water is shown in Figure

3. Cornell University tap water from the university water filtration plant was used for all experiments. Typical properties of this water are: pH = 7.5 ± 0.3; total hardness of 150 mg/L as $CaCO_3$; total alkalinity of approximately 110 mg/L as $CaCO_3$; and total organic carbon of 2.0 mg/L (Foote et al., 2012).

The water temperature was kept at 21ºC using an electronic thermistor and computer-controlled addition of hot or cold water. This constant-temperature water was aerated to reduce the concentration of supersaturated gases. Kaolin clay was added to provide a controlled level of turbidity, and a concentrated stock of this clay was dosed into the raw water tank via a computer-controlled pinch valve. The raw water turbidity was continuously sampled and measured with a feedback control loop. This influent turbidity was set to 100 NTU with a coefficient of variation of ±5%. Both the hot/cold solenoid valves and the clay stock pinch valve were automated with process control software written in LabVIEW, as described by Weber-Shirk (2009).

Bench-scale treatment apparatus

A bench-scale experimental process train was used to treat the conditioned raw water via alum dosing, rapid mix, hydraulic flocculation, and upflow sedimentation. The sedimentation process included a floc blanket and an inclined tube settler. A diagram of the bench-scale treatment system is shown in Figure 4. Flow rates in the system were set by computer-controlled peristaltic pumps (Cole-Parmer, Vernon Hills, IL).

A laboratory-grade alum solution was prepared daily with distilled water. Initial experiments showed that an alum dose of 45 mg/L (4.23 mg/L as Al) was suitable to produce a majority of particles with settling velocities greater than the settle capture velocity of the tube settlers. A raw water flow of 11.9 mL/s was used in all experiments. Raw water and alum were mixed by flowing through a 1 m length of 4.8 mm ID coiled tube with an energy dissipation rate of 0.1 W/kg.

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 a hydraulic residence time θ of 155 s. The Reynolds number for the tube flocculator was 1590, ensuring that laminar flow was maintained. For laminar conditions, the collision potential of a flocculator is proportional to $G\theta\phi_{Floc_0}^{2/3}$ where G is the average velocity gradient in the flocculator, θ is hydraulic residence time, and ϕ_{Floc_0} is the volume fraction of the primary particles, which is itself proportional to the concentration of clay and alum present in the system (Weber-Shirk and Lion, 2010). In these experiments, ϕ_{Floc0} was equal to 4.3×10^{-5}. The velocity gradient G in Equation (11) was based on the measured head loss through the flocculator:

$$G = \sqrt{\frac{gh_L}{\theta\nu_{Water}}} \tag{11}$$

The hydraulic residence time is based on the flow rate and geometry of the flocculator:

$$\theta = \frac{\pi D^2 L}{4Q} \tag{12}$$

Equations (11) and (12) were combined to calculate the value of $G\theta$.

$$G\theta = \frac{D}{2}\sqrt{\frac{\pi g h_L L}{Q\nu_{Water}}} \tag{13}$$

The value of $G\theta$ for the tube flocculator in this study was 15500. Although this value is on the low end of the range commonly used for hydraulic flocculators, it performed well in these experiments because the floc volume fraction was relatively high with 100 NTU raw water.

In a manner comparable to the experimental system described by Hurst et al. (2010), the sedimentation process consisted of an upflow clarifier with a floc blanket. The sedimentation tank upflow velocity was 1.2 mm/s and was set to be close to the optimal upflow velocity for floc blanket turbidity removal determined by Hurst et al. (2010). The height of the floc blanket was controlled by a floc wasting pump, which continuously pumped solids from the floc blanket at a height 15 cm below the water level at the top of the column. All experiments presented in this paper were performed with a floc blanket. From the top of the sedimentation column, water flowed to one of three possible paths:

1. Some water was pulled through a tube settler inclined at $\alpha = 60°$ at a rate set by the tube settler pump, making the tube settler velocity independent of the total system flow rate. The turbidity of this water was measured downstream of the tube settler.
2. Some water was drawn off the top of the sedimentation column to sample the turbidity above the floc blanket. This allowed the tube settler influent water to be tested so that the performance of the tube settler could be quantified.
3. The remainder of the flow passed over an overflow weir and was discharged.

Data acquisition and analysis

Turbidity readings were recorded at 5 s intervals using Micro TOL in-line turbidimeters (HF Scientific Model 20053, Ft. Myers, Florida) from the raw water tank; the floc blanket clarified effluent (i.e. the suspension within the sedimentation tank above the floc blanket); and the tube settler effluent. For experiments with small tube settler flow rates, a reservoir was used to accumulate tube settler effluent for sampling. Flow accumulated in a mixed container and was intermittently pumped through the tube settler effluent turbidimeter at 50 mL/min. Both mixing of the sample reservoir and the high sampling flow rate were employed to prevent settling of particles in the reservoir or the turbidimeter vial. Data was logged with the LabVIEW process controller software that also controlled the solenoid valves, pinch valves, and peristaltic pumps in the bench-scale apparatus.

Particle removal is reported below in terms of negative log fraction remaining, pC^*. This parameter is often called "log removal" and is defined by Equation (14):

$$pC^* = -\log\left(\frac{C_{Effluent}}{C_{Influent}}\right) \tag{14}$$

The pC^* parameter is a convenient dimensionless measure of particle removal efficiency. In this study, $pC^*$was calculated for overall removal efficiency of the floc blanket and tube settler ($pC^*_{Overall}$), for the floc blanket ($pC^*_{FlocBlanket}$), and for the tube settler ($pC^*_{TubeSettler}$). By definition, $pC^*_{Overall}$ is the sum of $pC^*_{TubeSettler}$ and $pC^*_{FlocBlanket}$.

RESULTS AND DISCUSSION

Replicability and stability of the bench-scale apparatus

Four replicate experiments were carried out to confirm that a floc blanket could be formed consistently in the upflow clarifier, and to obtain baseline performance data once steady-state was reached. Achieving consistent performance in these control experiments enhanced the ability to identify cases where floc roll-up caused an elevated effluent turbidity. Each replicate experiment used a 25.4 mm diameter tube settler downstream of the upflow clarifier. Two of the four trials were performed using a reservoir to sample the tube settler effluent turbidity. Exemplary results from one of these four tests are shown in Figure 5. Region A in the figure shows the period of floc blanket formation, before the system reaches steady-state performance in Region B.

The results indicated that the bench-scale system could produce replicable data. Once the system reached steady state, good baselines were observed for all measured turbidity values as shown in Figure 5. For four replicate trials, the raw water was maintained at around 101.4 NTU with an average coefficient of variation of 5%, and the clarified effluent was consistently around 11.4 NTU ± 13% after the floc blanket had formed. The tube settler effluent was 0.22 NTU ± 43%; however, this higher variability was considered acceptable given the small magnitude of the effluent turbidity. The tube settler effluent data from the reservoir trials was consistent with the data from the non-reservoir trials, indicating that the sampling reservoir did not introduce a systematic bias into the tube settler turbidity data.

Floc roll-up experiments

Table 1 summarizes the experimental conditions used to investigate floc roll-up. The tube settlers were sized using Equation (1) to maintain a constant settle capture velocity of 0.10 mm/s. The flow rate through the tube settler was controlled by a peristaltic pump. This flow rate Q was calculated from:

$$Q = V_{Settle}\left(\frac{L}{D}\cos\alpha + \sin\alpha\right)\pi\frac{D^2}{4} \tag{15}$$

where D is the inner diameter of the tube, V_{Settle} is the settle capture velocity set at 0.10 mm/s, and α is the angle of inclination set at 60°. Because the settle capture velocity was held constant, each tube settler described in the table would be expected to have identical turbidity removal performance based on conventional design. Variations in performance therefore would show the effect of the floc roll-up failure mode on particles that would otherwise have been expected to be captured.

Figure 6 gives the measured pC^* as a function of velocity gradient at the tube wall for the experiments listed in Table 1. When velocity gradient increased, the performance of the system declined, while the performance of the floc blanket remained relatively consistent with an average pC^* of 1.12. At low velocity gradients, the overall system had a pC^* of 2 or greater, but this declined to just over 1 for higher velocity gradients. This effect was attributable to the tube settler, because there was no systematic variation in the particle-removal performance of the floc blanket.

Comparison to theoretical predictions

The results show a decrease in tube settler performance with increasing velocity gradient, despite the fact that each experiment had a settle capture velocity of 0.10 mm/s. The experimental observations are qualitatively consistent with model predictions - high velocity gradients were expected to cause flocs to roll up the inclined surface and thus increase effluent turbidity. Under the experimental conditions, the slide capture velocity usually controlled tube settler performance, which led to the variation observed in Figure 6 even though each tube settler had the same settle capture velocity.

Figure 7 shows the extent to which the roll-up phenomenon affected the tube settler in each experiment. The observed turbidity removal performance of the tube settler (as pC^*) is plotted against the ratio of the slide capture velocity V_{Slide} (estimated from Equation (10)) to the settle capture velocity V_{Settle} (fixed at 0.10 mm/s). The higher this ratio, the poorer the performance of the tube settlers, which suggests that the floc roll-up failure mode was indeed responsible for the decline in performance as velocity gradient increased. Note in the graph that the tube settler achieved good and relatively consistent performance until the capture velocity ratio reached a value of 1. Once the slide capture velocity was greater than the settle capture velocity, performance declined as more particles began to escape via floc roll-up.

Practical implications

The results presented above, along with the theoretical model proposed in Equation (10), suggest that the typical spacing of inclined settling devices can indeed be reduced. The following example depicts the possible material savings on sedimentation tanks by halving plate settler spacing. The length of plate settlers is typically about 20 times as long as the spacing. Conventional design guidelines suggest a spacing of 5 cm, resulting in plate lengths of approximately 1 m. Assuming an angle of inclination of 60°, 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 significantly lower the cost of construction.

Based on this insight, the AguaClara program at Cornell University has been using a design spacing of 2.5 cm for inclined plate settlers in upflow sedimentation tanks, for the affordable gravity-fed drinking water treatment plants it has implemented in seven towns in

Honduras. These plate settlers are designed for a capture velocity of 0.12 mm/s, and they perform well even with the reduced plate settler spacing and reduced tank depth (Smith, 2010).

For any water treatment application, the slide capture velocity could be calculated, and the spacing of the inclined settling device could then be selected to ensure that the slide capture velocity does not exceed the settle capture velocity. The minimum allowable spacing for plate settlers can be obtained by setting the settle capture velocity (Equation (1)) equal to the slide capture velocity (Equation (10)) and solving for the spacing:

$$D_{Min} \approx \frac{3}{sin^2\alpha}\frac{V_\uparrow}{V_C}d_{Floc_0}\left(\frac{18V_\uparrow\Phi\nu_{Water}}{gd_{Floc_0}^2}\frac{\rho_{Water}}{\rho_{Floc_0}-\rho_{Water}}\right)^{\frac{1}{D_{Fractal}-1}} \tag{16}$$

where $V_C = V_{Settle} = V_{Slide}$ and the constant 3 is used for the plate geometry rather than the 4 that would be used for tube geometry. Equation (16) is based on first principles and provides a basis for evaluating the influence of various parameters on the required spacing. The calculated spacing is the minimum value required to avoid the adverse effect of floc roll-up, based on the observation that performance degradation begins to occur when the slide capture velocity is greater than the settle capture velocity. The required spacing is a function of floc properties (primary particle density - ρ_{Floc_0}, fractal dimension - $D_{Fractal}$, primary particle diameter - d_{Floc_0}), water properties (viscosity - ν_{Water} and density - ρ_{Water}), upflow velocity - $V_\uparrow$, and desired capture velocity - V_C. Equation (16) is plotted in Figure 8 for a base case of 20° C water, 100 mg/L of clay particles with a diameter of $2\,\mu$m, plate settlers angled at 60°, capture velocity of 0.12 mm/s, and a fractal dimension of 2.3. Three other cumulative effect cases are also shown in Figure 8. In the second case, the clay is removed from the raw water and the primary particle is a 100 nm aluminum hydroxide precipitate. In the third case, the viscosity of water is also increased to that of 0° C water. In the fourth case, the fractal dimension is also decreased to 2.2. This analysis suggests that plate settler spacing could be much smaller for clay-alum flocs, but that larger spacing may be required for low-temperature water with flocs formed from smaller-size primary particles.

Although the fractal dimension is expected to be relatively constant for flocs that are formed under the same aggregation conditions, the dramatic impact of a small change in the fractal dimension suggests that further work to characterize the fractal dimension of flocs formed at water treatment plants would be beneficial.

CONCLUSIONS

The floc roll-up model describes a failure mechanism that prevents flocs from sliding along an inclined surface in the counter-current direction. This failure is caused by velocity gradients at the plate or tube wall, which create a fluid drag on the floc that opposes gravitational forces. A theoretical model is presented as an analysis of this failure mechanism, leading to a "slide capture velocity" for situations in which floc roll-up controls the performance of inclined settling devices. Consistent with model predictions, experimental inclined tube settlers showed a decline in performance with increasing velocity gradient, even though traditional design equations predict that the settle capture velocity and performance of these tube settlers should have been constant. Tube settler turbidity removal deteriorated when the slide capture velocity was larger than the settle capture velocity. This failure mode explains the rationale for setting a minimum value for the spacing of inclined settling devices, but it appears that there are opportunities to use smaller spacings to create more economical sedimentation tanks. Further work to characterize the properties of flocs from a variety of water sources, coagulant dosages, and types of coagulants would be helpful to determine the limiting case for plate settler spacing or tube settler diameter.

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