Parameters affecting steady-state floc blanket performance

Matt Hurst, Monroe Weber-Shirk and Leonard W. Lion

ABSTRACT

A laboratory-scale reactor was used to simulate a water treatment process sequence of rapid mix, hydraulic flocculation, upflow clarification with a floc blanket, and lamellar sedimentation to accomplish removal of colloidal particles. This study focused on variables affecting performance of the floc blanket including: provision of hydraulic flocculation, raw water turbidity, coagulant dose, upflow velocity through the floc blanket, and bulk density and solids concentrations of the floc blanket. An upflow clarifier velocity between 1.0 and 1.3 mm s^{-1} produced the best floc blanket performance for turbidities studied between 10 and 200 NTU while an upflow velocity between 0.6 and 0.8 mm s^{-1} produced the best floc blanket performance at 500 NTU. The results show that overall particle removal efficiency improved with increasing hydraulic flocculator residence time and energy dissipation rate. Particle removal efficiency improved with increasing floc blanket depth for floc blanket depths between 15 and 75 cm. Lamellar sedimentation with a capture velocity of 0.12 mm s^{-1} is a key component in improving clarifier performance when utilizing a floc blanket.

Key words | floc blanket, flocculation, performance, steady-state, tube settlers

Matt Hurst
Monroe Weber-Shirk (corresponding author)
Leonard W. Lion
School of Civil and Environmental Engineering,
Cornell University,
Hollister Hall,
Ithaca NY 14853-3501,
USA
Tel.: +1 607 255-8445
Fax: +1 607 255-9004
E-mail: *mw24@cornell.edu*

NOMENCLATURE

$A_{clarifier}$	cross-sectional area of the clarifier (L^2)
A_s	normal area of the tube settler (L^2)
C_{in}	influent concentration (M/L^3)
C_{out}	effluent concentration (M/L^3)
d	inner diameter of tubing (L)
D	tubular flocculator coil diameter (L)
f_{ratio}	ratio of the friction factor for curved tubing versus that for straight
g	acceleration due to gravity (L/t^2)
G	velocity gradient in viscous subrange (1/t)
h_{floc}	depth of floc blanket (L)
h_l	head loss (L)
h_{water}	depth of water that would produce the same pressure as h_{floc} (L)
L	length of tubing (L)
N_{De}	Dean number
pC*	− log fraction remaining = [−log(C_{out}/C_{in})] (pC^* is the same as what is referred to as log removal in the literature)
Q	flow rate (L^3/t)
V	average axial velocity of flow in the tube flocculator
V_c	capture velocity of the tube settler (L/t)
V_{up}	upflow velocity in the clarifier (L/t)
α	angle of tube settler with respect to the horizontal
ε	energy dissipation rate (L^2/t^3)
θ	hydraulic residence time (t)
$\theta_{clarifier}$	hydraulic residence time of fluid in upflow clarifier (t)
$\theta_{floc\ fluid}$	hydraulic residence time of fluid in floc blanket (t)
ν	kinematic viscosity (L^2/t)

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ρ_{water}	density of water (M/L^3)
$\rho_{bulk\ floc}$	bulk density of floc blanket (M/L^3)
Φ	porosity of the floc blanket

INTRODUCTION

A central goal in water treatment processes is to remove colloidal particles. Colloidal particles interfere with disinfection, negatively impact drinking water quality, and are indicative of the potential presence of pathogenic organisms. A large portion of colloidal particle removal in drinking water treatment plants occurs in sedimentation either in the sedimentation basin or through lamellar sedimentation. In this research, the removal of colloidal particles was studied in an upflow floc blanket clarifier combined with lamellar sedimentation.

At appropriate upflow velocities, a fluidized bed of concentrated flocs with a visible floc–water interface between the concentrated floc layer and a relatively clear overlying effluent layer forms in upflow sedimentation basins. Upflow clarification with a floc blanket is thought to enhance particle removal compared with conventional upflow clarification by providing an increased likelihood of particle–particle interactions that can result in further flocculation of particles and filtration-like removal of small particles (Miller & West 1968; Reynolds & Richards 1996; Tchobanoglous *et al.* 2006).

Influent conditions in this study were selected to represent surface waters in a warm climate with dry and wet periods. A value of 10 NTU corresponds to a dry period with relatively little rainfall. A turbidity of 500 NTU was chosen to be representative of a storm surge event during a period of rainfall. Although colder temperatures were not tested, Lau (1994) has shown that, as temperature decreases, the settling velocity of particles increases.

The objective of this research was to characterize and optimize floc blanket performance at steady-state with respect to the following parameters: alum dose at different influent turbidities, upflow velocity in the clarifier, floc blanket depth and the provision of hydraulic flocculation before upflow sedimentation. Although constant dosing on a pilot and laboratory-scale has been documented in the literature (Miller & West 1968; Zhang *et al.* 2006), this study is unique with respect to: the range over which each parameter was evaluated; the continuous monitoring of effluent turbidity from both the floc blanket clarifier and subsequent tube settlers; and stringent control of the energy dissipation rate and residence time in the flocculator and floc blanket clarifier.

Gould (1969) and Sung *et al.* (2005) identified upflow velocity as critical in determining floc blanket stability and performance utilizing mass flux theory. If upflow velocity is too high, a large proportion of particles will be washed out making it difficult to establish a floc blanket. If the upflow velocity is too low, sedimentation can irreversibly change the nature of the flocculated particles and the effectiveness of treatment (Arai *et al.* 2007). The average upflow velocity in a clarifier (V_{up}) is given by Equation (1), where Q is the flow rate and $A_{clarifier}$ is the cross-sectional area. Crittenden (2005) recommends an upflow velocity between 1.4 and 2.8 mm s^{-1} for a combined floc blanket–plate settler system.

$$V_{up} = \frac{Q}{A_{clarifier}} \tag{1}$$

Floc blankets are reported to be effective at removing colloidal particles and organic matter for a wide range of influent qualities (Lin *et al.* 2004). For high turbidity water, some investigators have recommended that the majority of the turbidity should be removed in a pre-sedimentation tank with a suggested residence time of 90 minutes (Chen *et al.* 2002). For high turbidity source waters (>200 NTU), Su *et al.* (2004) reported that treatment was feasible with the addition of a pre-sedimentation tank. In contrast, Sung *et al.* (2005) reported a stable floc blanket could be formed from 450 NTU source water without the need for a pre-sedimentation tank or two-stage clarifier.

At very low turbidities (<5 NTU) floc blankets have been reported to be easily washed out (Chen *et al.* 2006). Chen *et al.* (2002) observed stable floc blanket formation from raw waters with turbidity between 4 and 10 NTU in full-scale clarifiers, but during a low turbidity period (2–3 NTU), floc blankets gradually lost solids until no floc blanket remained.

At conditions of low turbidity, flocculation processes are less efficient in creating large flocs, and solids loading to a floc blanket clarifier are significantly reduced. Utilizing plate settlers above the floc blanket could extend the range of floc blanket utility because particles that are captured by the plate settler will settle and fall back into the underlying floc blanket, thereby increasing solids concentration and solids residence time in the floc blanket.

Flocculation prior to the upflow clarifier is expected to affect the density and size of entering particles, ultimately affecting floc size distribution and concentration in the blanket. The ability of particles to remain suspended in a floc blanket depends on the settling velocity of the flocculated particles counterbalanced by the upflow velocity in the clarifier (Gregory *et al.* 1996; Head *et al.* 1997). The density and size of a flocculated particle are functions of how the floc was formed, thus energy dissipation rate and residence time in a flocculator prior to the upflow floc blanket clarifier could be important parameters that influence particle removal.

The use of lamellar (or plate) settlers can potentially allow a reduction in the size of vertical flow sedimentation tanks while maintaining a similar standard of treatment (Saleh & Hamoda 1999). Plate settlers are designed for capture of particles with a specific terminal settling velocity. Schulz & Okun (1984) recommend capture of particles with terminal settling velocities between 0.12 and 0.36 mm s^{-1}. For this experiment, a capture velocity of 0.12 mm s^{-1} was selected as it is the lowest recommended design capture velocity of Schulz & Okun (1984) and, in theory, will give the best particle removal in lamellar sedimentation.

MATERIALS AND METHODS

Set-up and control of parameters

Conditions of constant input turbidity were created using a concentrated kaolin clay suspension diluted with temperature controlled, aerated tap water (Figure 1) to produce a raw water source for treatment.

Turbidity was controlled by process control software that compared turbidity readings with the target level. When the turbidity dropped below the target level, a signal to the output control box opened a solenoid valve allowing

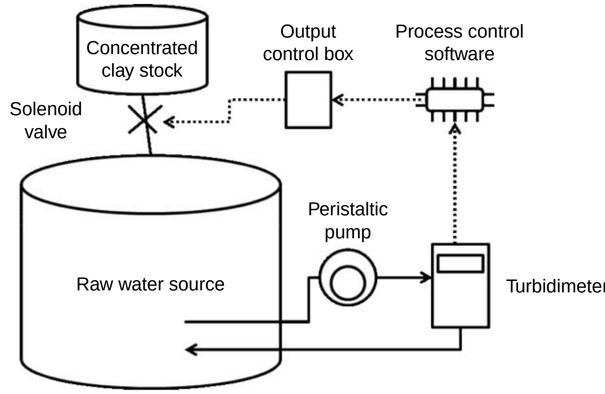

Figure 1 | Schematic showing how influent turbidity is controlled using process control software (Weber-Shirk 2008).

release of a small amount of concentrated clay stock suspension into the raw water source (Figure 1). Input turbidity had a coefficient of variation of ±3%.

The pH of the raw water source remained relatively constant at 7.5 varying by no more than 0.3 pH units. Total hardness (150 mg l^{-1} as $CaCO_{3(s)}$), total alkalinity (111 mg l^{-1} as $CaCO_{3(s)}$) and total organic carbon (2.0 mg l^{-1}) were obtained from the 2008 consumer water quality report for Cornell University Water System (City of Ithaca 2008).

The alum coagulant was prepared daily to avoid ageing (Rossini *et al.* 1999). Raw water was combined with a desired amount of alum, and rapid mix was achieved by directing the flow through a tube 4.8 mm ID (inner diameter), 1 m in length with energy dissipation rates varying between 0.05 and 1.10 W kg^{-1}, depending on flow (Figure 2).

Flow from the rapid mix entered coiled tube flocculators (inner diameter, $d = 9.5$ mm). The residence time (θ) in the flocculator was controlled by the length of the tube flocculator (L) (Equation (2)). The energy dissipation rate (ε) is the energy loss per unit time and can be calculated from the product of head loss through the flocculator (h_l) and acceleration due to gravity (g) per unit residence time (Equation (3)). The velocity gradient, G (s^{-1}), is related to the energy dissipation rate and kinematic viscosity (ν) (Tambo & Hozumi 1979) (Equation (4)).

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

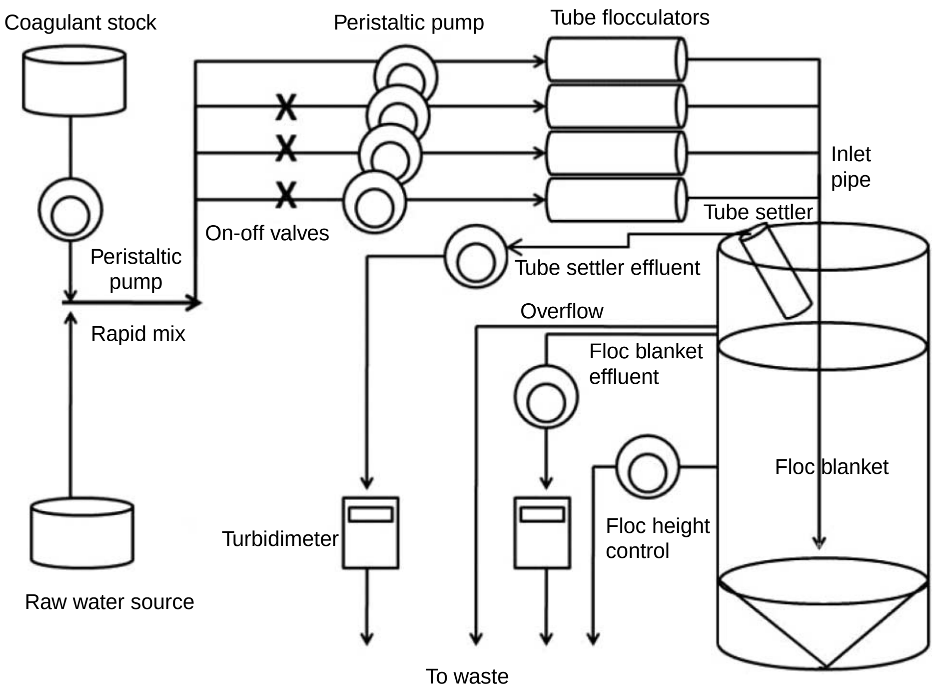

Figure 2 | Schematic of flow through laboratory scale plant.

$$\varepsilon = \frac{gh_l}{\theta} \tag{3}$$

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

Coiled tubes develop secondary flow circulation (Zhou & Shah 2006) causing additional mechanical energy loss. Liu & Masliyah's model (1993) for Dean numbers less than 5,000 gives the ratio of the friction factor of curved versus straight tubing (f_{ratio}) based on the calculated Dean number (N_{De}) (Equations (5) and (6))

$$N_{\text{De}} = \frac{Vd}{\nu}\left(\frac{d}{2D}\right)^{(1/2)} \tag{5}$$

$$f_{\text{ratio}} = \frac{1 + \left[0.0908 + 0.0233\left(\frac{d}{D}\right)^{1/2}\right]N_{\text{De}}^{1/2} - 0.132\left(\frac{d}{D}\right)^{1/2} + 0.37\left(\frac{d}{D}\right) - 0.2}{1 + \frac{49}{N_{\text{De}}}} \tag{6}$$

where: D is the coil diameter and V is the average axial velocity of flow in the pipe.

After tube flocculation, the flow was released 8 cm from the bottom of the floc blanket reactor. The floc blanket elevation was controlled by continuously removing fluid at a desired height in the upflow column using a flow equal to one sixth the total flow rate in the reactor. Other effluent was removed from the reactor using a combination of controlled flow through a tube settler (used to mimic lamellar sedimentation) and an overflow weir 2 cm from the top of the reactor.

Data acquisition and sampling

Turbidity readings were obtained for continuous sampling of both the clarified fluid above the floc blanket and for the effluent from the tube settler using Micro TOL Turbidimeters (HF Scientific Model 20053, Ft Myers, Florida). The tube settler was located 5 cm from the top of the reactor and was utilized to create particle capture velocities that would be comparable to the plate settler capture velocities in full-scale water treatment plants. Raw water turbidity was also logged and compared with the effluent data to determine particle removal efficiencies.

A peristaltic pump pulled water from the top of the tube settlers. The capture velocity (V_c) in the tube settler was set equal to 0.12 mm s^{-1} (Equation (7)) by using an appropriate flow rate (Equation (8)) (Schulz & Okum 1984)

$$V_\alpha = \frac{V_c(L\cos(\alpha) + d\sin(\alpha))}{d} \quad (7)$$

$$Q = \frac{L\cos(\alpha) + d\sin(\alpha)}{d}\left(\pi\left(\frac{d}{2}\right)^2 n\right)V_c \quad (8)$$

where: Q is the pump flow rate, d is the inner diameter of the tube ($d = 9.5$ mm), n is the number of tubes utilized ($n = 6$), L is the length of the tube ($L = 19$ cm), α is the angle of orientation ($\alpha = 60°$), and V_α is the average fluid velocity in the tube.

Performance analysis

Data presented within this paper were for conditions of floc blanket steady-state. Steady-state was defined as occurring when the floc blanket was at full height and floc blanket and tube settler effluent performance over three hydraulic residence times had a coefficient of variation less than ±10%. Data points collected at steady-state were the average over three hydraulic residence times as shown in Figure 3.

In this study, the negative logarithm of the fraction of particles remaining, pC^* (Equation (9)), was utilized as a way to characterize and compare performance of the floc blanket in a combined floc blanket-plate settler. pC^* is synonymous with what is sometimes termed 'log reduction' in the literature. Although pC^* is typically utilized to characterize removal of biological pathogens, some studies have utilized pC^* to characterize log removal of turbidity (Carlson 2001).

$$pC^* = -\log\left(\frac{C_{out}}{C_{in}}\right) \quad (9)$$

Bulk density of the floc blanket was measured using a pycnometer and solids concentration were obtained as described in *Standard Methods* (2005). A linear relationship between solids concentration (C_s), and bulk density ($\rho_{bulk\ floc}$) in the floc blanket was observed (Equation (10)) over a wide range of floc formation conditions (Figure 4)

$$\rho_{bulk\,floc} = 0.687\,C_s + \rho_{water} \quad (10)$$

where ρ_{water} is the density of water.

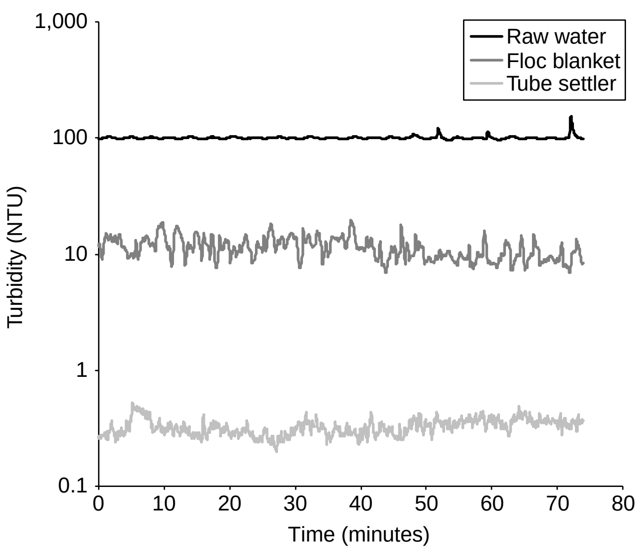

Figure 3 | Continuously sampled turbidity readings for raw water influent, clarified water above the floc blanket and the tube settler effluent at a dose of 45 mg l^{-1}. The upflow velocity in the floc blanket was 1.2 mm s^{-1} and the capture velocity in the tube settler was 0.12 mm s^{-1}. The hydraulic residence time in the clarifier was 13 minutes.

RESULTS AND DISCUSSION

Change in solids concentration in floc blanket with upflow velocity

Solids concentrations in the floc blanket were measured at a height of 51 cm for a fully built floc blanket of 75 cm.

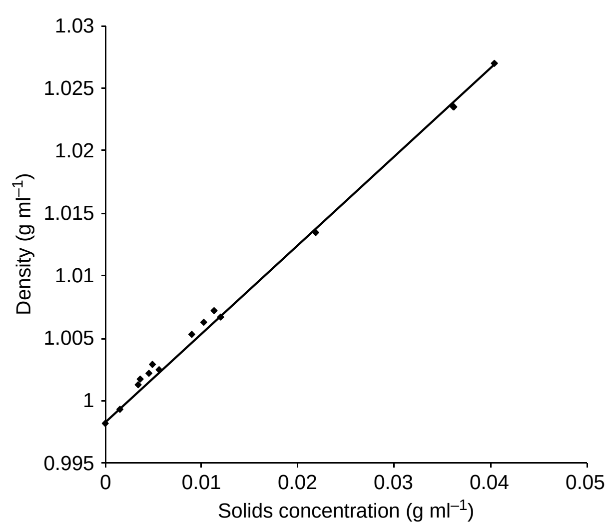

Figure 4 | Relationship between floc blanket density and solids concentration ($r^2 = 0.98$).

Results are shown in Figure 5(a). The floc blanket solids concentration between 20 and 55 hours after formation had a coefficient of variation of ±3% which is consistent with the observations of Gould (1969) that solids concentration throughout the middle portion of the floc blanket was uniform. Measured solids concentrations at different upflow velocities and heights within the floc blanket are shown in Figure 5(b).

Energy dissipation in the floc blanket

A force balance requires the head loss through a fluidized bed to be proportional to the difference between the bulk density of the fluidized bed ($\rho_{\text{bulk floc}}$) and the density of water (ρ_{water}). Head loss, h_l, through the floc blanket with height (h_{floc}) is given by

$$h_l = h_{\text{floc}} \frac{\rho_{\text{bulk floc}} - \rho_{\text{water}}}{\rho_{\text{water}}} \tag{11}$$

Combining Equations (11) and (10) gives:

$$h_l = h_{\text{floc}} \frac{0.687 C_s}{\rho_{\text{water}}} \tag{12}$$

The hydraulic residence time in the floc blanket ($\theta_{\text{floc fluid}}$) can be defined in terms of the height of the floc blanket (h_{floc}), the upflow velocity of the fluid (V_{up}) and the porosity of the floc blanket (Φ).

$$\theta_{\text{floc fluid}} = (\Phi) \frac{h_{\text{flow}}}{V_{\text{up}}} \tag{13}$$

The porosity of the floc blanket was estimated to be approximately 85% based on a 30 minute settling test. Substituting head loss, h_l, and hydraulic residence time, $\theta_{\text{floc fluid}}$, into the energy dissipation rate relationship (Equation (3)) allows floc blanket energy dissipation rate to be expressed in terms of upflow velocity and solids concentrations (Equation (14)).

$$\varepsilon = \frac{g V_{\text{up}}}{(\Phi)} \frac{0.687 C_s}{\rho_{\text{water}}} \tag{14}$$

From Equation (14) the energy dissipation rate in a floc blanket can be compared based on the average solids concentrations for each upflow velocity found in Figure 5. The values of G and $G\theta_{\text{floc fluid}}$ for the floc blanket could then be estimated for a floc blanket based on the hydraulic residence time in the floc blanket and the value of G (Equation (4)) calculated based on the energy dissipation rate (Equation (14)) as shown in Figure 6. The flow was laminar in the floc blanket, so it is reasonable to use G notation to describe the flocculation of clay in the floc blanket.

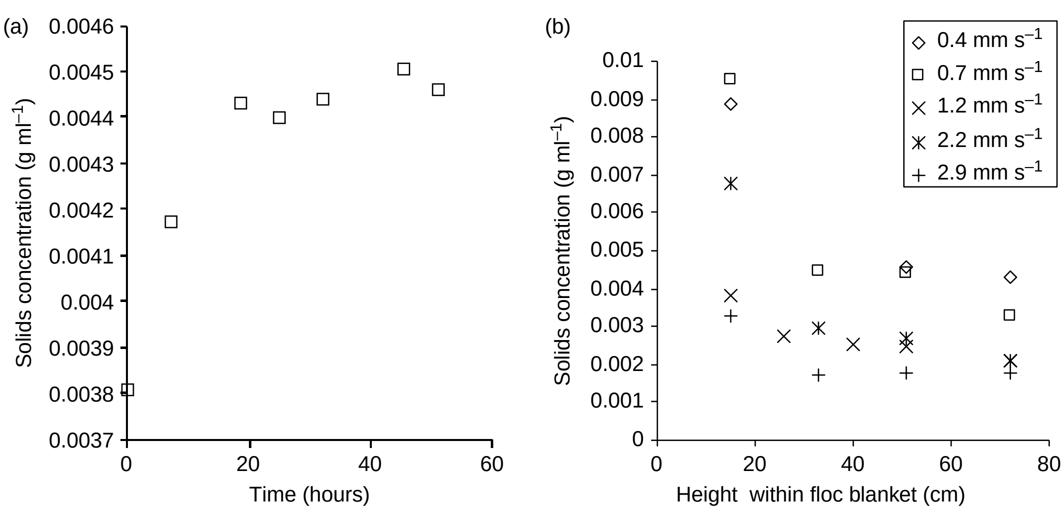

Figure 5 | (a) Solids concentration sampled at a height of 51 cm from the bottom, starting at time zero when the floc blanket reached a target height of 75 cm, with an upflow velocity of 1.4 mm s^{-1}; (b) change in the solids concentration with respect to height within the floc blanket (75 cm total height) in the reactor for several upflow velocities. Influent turbidity was 100 NTU and the alum dose was 55 mg l^{-1} for both (a) and (b).

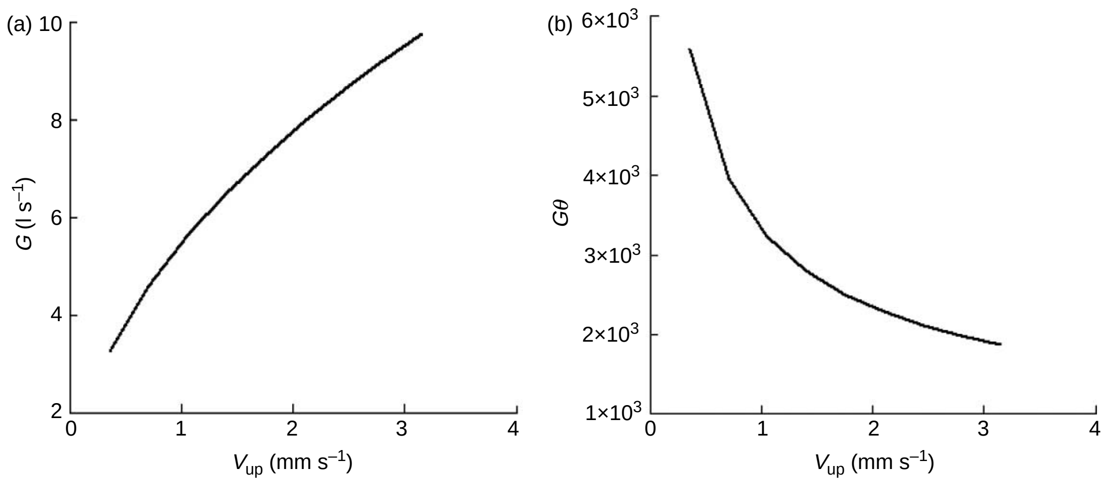

Figure 6 | (a) G as a function of upflow velocity (b) $G\theta_{floc\ fluid}$ as a function of upflow velocity for a floc blanket depth of 75 cm.

Energy dissipation in tube flocculators

Head loss across the tube flocculators was measured for flows ranging from 1.7 ml s^{-1} to 15 ml s^{-1} with a diameter of coil (D) of 12.5 cm, and an inner tube diameter (d) of 0.95 cm. The total length of tubing was 16 m of which 12.5 m was coiled. All flow was laminar with a maximum Reynolds number of 2,200. The head loss data measured in laboratory agreed well (within a coefficient of variation of ±4.5%) with values calculated from the Liu and Masliyah correlation (Equation (6)).

Energy dissipation (ε) (Equation (3)) and the velocity gradients for the viscous subrange (G) (Equation (4)) were calculated and compared with the measured G values based on measured head loss (Figure 7(a)). The resulting value of $G\theta$ is shown in Figure 7(b). The values of $G\theta$ and G presented in Figure 7 are representative for the range of flow rates through one tube flocculator utilized in this experiment. $G\theta$ would be independent of flow rate for laminar flow through a straight tube flocculator, but the nonlinear effect of tube curvature on energy dissipation causes $G\theta$ to increase with flow rate.

Energy dissipation rates in the flocculator (Figure 6(a) and (b)) were orders of magnitude higher than energy dissipation rates in the floc blanket (Figure 7(a) and (b)).

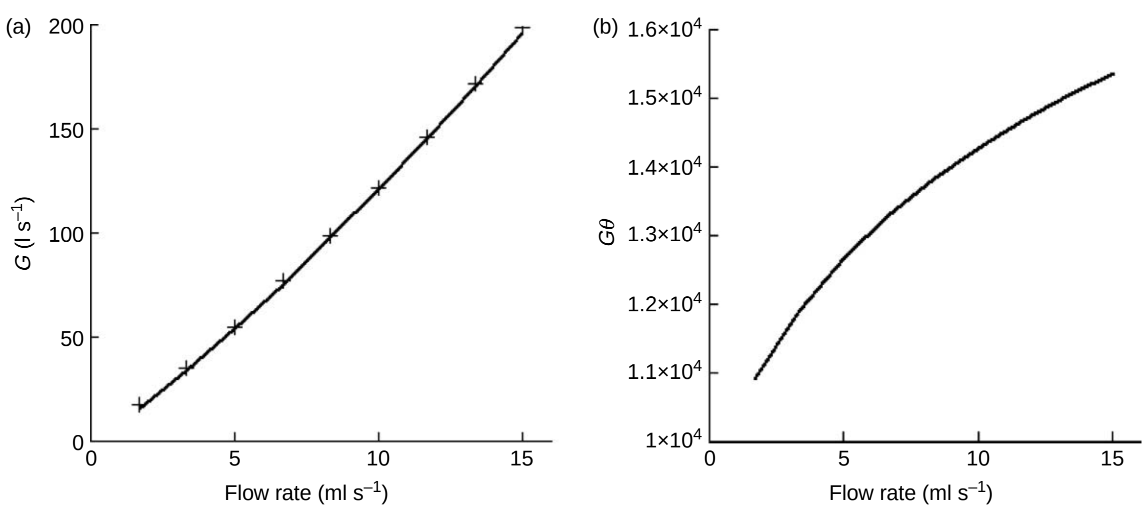

Figure 7 | (a) Measured G (crosses) compared with theoretical predictions (line) based on Lui & Masliyah (1993) for laminar flow through coiled tubes; (b) heoretical $G\theta$ versus flow rate.

Removal of colloid particles inside the floc blanket could still potentially occur even with lower energy dissipation rates because of relatively long floc blanket hydraulic residence times and the much higher floc volume fraction that reduces the time required for particle–particle collisions.

Characterizing floc blanket performance at steady-state

Effect of upflow velocity on floc blanket performance

The upflow velocity in the sedimentation column was varied while alum dosage, turbidity and floc blanket height (75 cm) were held constant. Figure 8 shows the steady-state turbidity in the fluid above the floc blanket and in the effluent from the tube settler for influent turbidities of 100 and 500 NTU. Each point represents the average of observations taken over three hydraulic residence times and the error bar represents the standard deviation over this average.

As seen in Figure 8 for 100 and 500 NTU water, a range of upflow velocities produced a floc blanket with a relatively clear effluent above. The optimum upflow velocities ranged between 1.0 and 1.3 mm s^{-1} and 0.6 and 0.8 mm s^{-1} for influent turbidities of 100 NTU and 500 NTU, respectively. Upflow velocities outside the optimal range increased turbidity and performance variability.

In extreme cases of low upflow velocity, the velocity was not sufficient to counteract the terminal settling velocity of the flocculated particles. The bottom 25 cm of the upflow clarifier was no longer fluidized and instead small flow channels formed in the settled sludge. The small flow channels with their associated high velocities likely caused floc break up and the production of small floc particles that could not be captured by the tube settlers. Increased variability in the effluent turbidity could be attributed to variability in channelling through the settled sludge over time. For very high upflow velocities, the upflow velocity was greater than most of the settling velocities of the flocculated particles so that the floc–water interface became blurred and the suspension more dilute.

Upflow velocity and floc blanket height (75 cm) were held constant while alum dose was varied. Each floc blanket was reformed to a height of 75 cm. The effects of variable alum dose were tested at 100 NTU and 200 NTU influent turbidities (Figure 9).

The optimum alum doses (dosages resulting in best performance) for 100 NTU and 200 NTU water were approximately 45 mg l^{-1} and 65 mg l^{-1}, respectively (Figure 9). However, performance did not significantly deteriorate at higher dosages of alum in either case. Optimization of alum dose was also tested for a higher influent turbidity (500 NTU) and a lower influent turbidity (10 NTU) in Figure 10. For optimal alum dosage at 500 NTU, the optimal upflow velocity occurred between 0.6 and 0.8 mm s^{-1} and between 1.0 and 1.3 mm s^{-1} for 10 NTU water (data not shown).

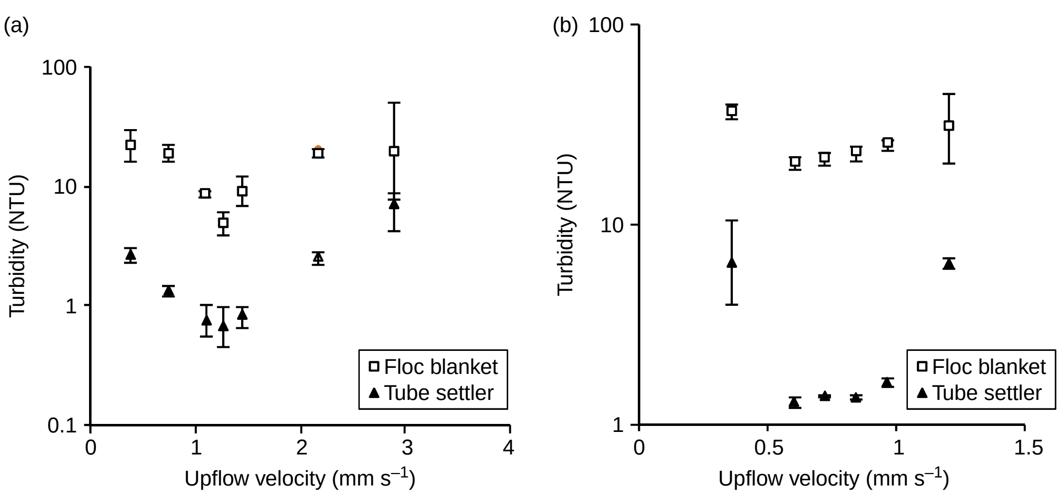

Figure 8 | (a) Effluent turbidity of tube settlers and floc blanket at 100 NTU and 55 mg l^{-1} alum dosage; (b) effluent turbidity of tube settlers and floc blanket at 500 NTU and 95 mg l^{-1} alum dosage.

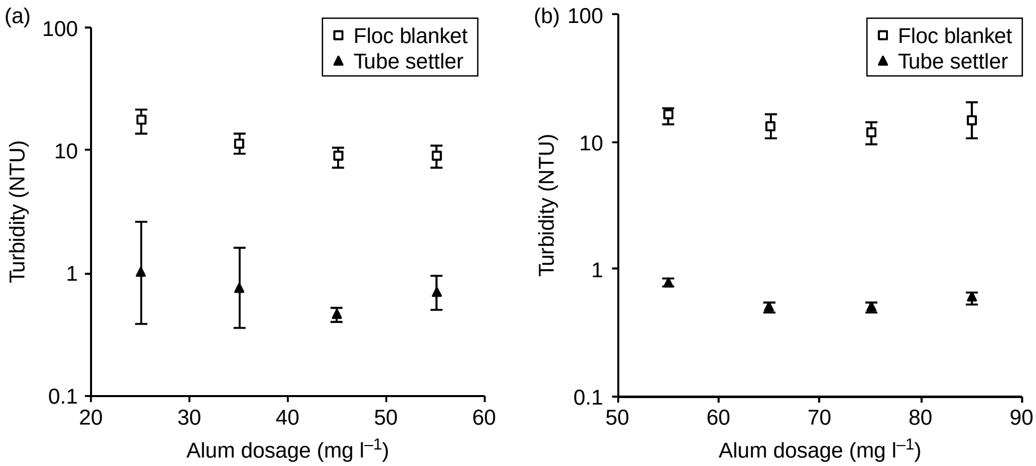

Figure 9 | (a) Effect of alum dosage on 100 NTU water at an upflow velocity of 1.2 mm s^{-1}; (b) effect of alum dosage on 200 NTU water at an upflow velocity of 1.2 mm s^{-1}.

At the influent turbidity of 500 NTU, the tube settler effluent did not fall below 1 NTU; however, a pC^* of 2.5 was achieved.

Underdosing of alum could decrease the size and the amount of flocculated particles entering the floc blanket. Thus, a higher proportion of particles would not be captured by tube settlers or the clarifier. Overdosing showed little effect on floc blanket performance for the range of dosages tested.

Effect of floc blanket height on floc blanket performance

Effluent turbidity was monitored over a range of floc blanket heights. Conditions for these experiments were: alum dosage 45 mg l^{-1}, influent turbidity 100 NTU, and an upflow velocity of 1.2 mm s^{-1} with varying G and $G\theta$. A control (no tube flocculation) experiment was also performed in which coagulated particles were introduced directly into the upflow reactor without flocculation (Figure 11). Miller & West (1968) observed increased removal efficiency with increasing blanket height and these observations were confirmed in this study (Figure 11).

In contrast to the findings of Gregory (1979) and Casey *et al.* (1984), data obtained in this study suggest that effective implementation of lamellar settlers above a floc blanket can significantly improve effluent performance. Tube settlers above a floc blanket that is deeper than 65 cm could achieve turbidities below 1 NTU (Figure 11).

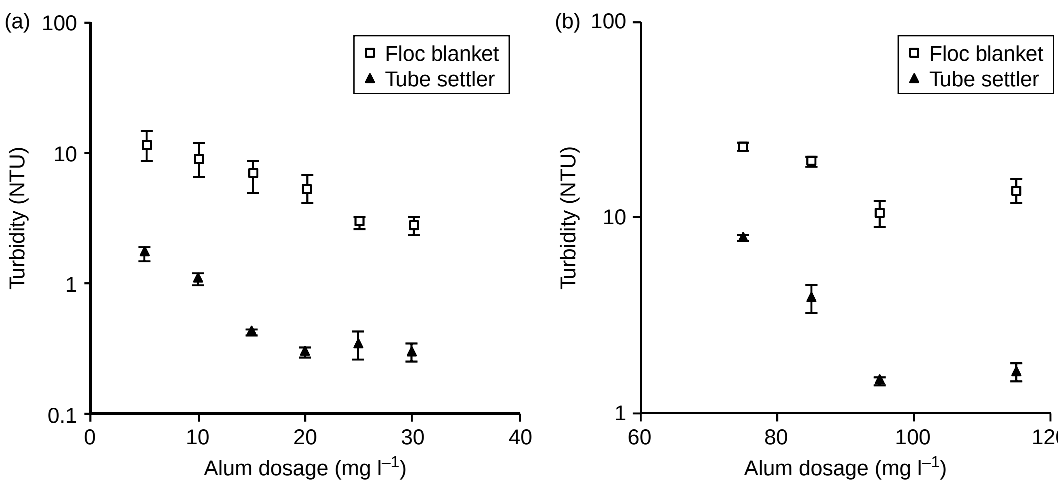

Figure 10 | (a) Effect of alum dosage on 10 NTU water at an upflow velocity of 1.2 mm s^{-1}; (b) effect of alum dosage on 500 NTU water at an upflow velocity of 0.8 mm s^{-1}.

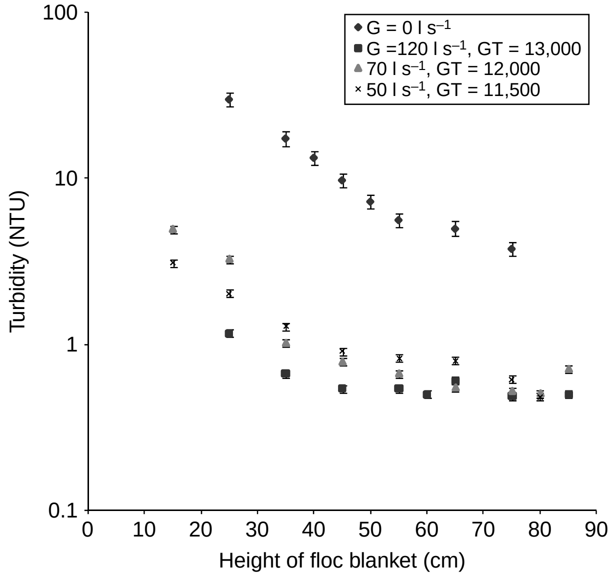

Figure 11 | Effect of floc blanket height and provision of flocculation in the flocculator on tube settler effluent turbidity.

Effect of flocculator and floc blanket energy dissipation rate on floc blanket performance

The effect of varying energy dissipation rates in the flocculator on floc blanket performance was evaluated while maintaining the parameter $G\theta$ in each flocculator relatively constant with relevant data shown in Figure 11. For example, splitting the flow from one tube to two in parallel that were the same length would double the hydraulic residence time (θ), but would decrease the velocity gradient (G) by a factor of approximately two (Figure 7(b)).

Floc blanket performance increased with increasing energy dissipation rate in the flocculator especially between a floc blanket height of 35 and 65 cm for all cases studied (Figure 11). Floc blanket performance for heights above 45 cm for the cases where there was a tube flocculator present had a coefficient of variation of ±20% and performance between 55 cm and 75 cm had a coefficient of variation of ±20% for the case with no prior flocculation.

Energy dissipation rate in the flocculator influences floc strength. Francois (1987) found an increase in floc strength for flocs formed with higher energy dissipation rates as well as stronger flocs for increased residence time in the flocculator. If the particles formed in the flocculator at higher energy dissipation rates were stronger they would be less prone to break up in the floc blanket. Given the long solids residence times in the floc blanket, floc break up could be an important contributor to effluent turbidity at blanket heights greater than 45 cm. The velocity gradients in the floc blanket (predicted from Equations (14) and (4) shown in Figure 7(a)) were less than $10\,s^{-1}$. Thus, floc break up due to fluid–particle interactions would not be expected to be significant in the floc blanket. However, it is possible that particle–particle interactions are a significant source of high local stresses that result in floc break up.

The removal efficiency of particles, as expressed by pC^*, for floc blanket effluent and for tube settler effluent was determined for the control (no hydraulic flocculation) case (Figure 12).

Without the benefit of a tube flocculator, particles entering the floc blanket were coagulated with alum but not flocculated. Nevertheless, the floc blanket formed in the upflow clarifier and effluent turbidity decreased as the floc blanket increased in height. Particle removal expressed as pC^* was linear with blanket height up to a height of 55 cm. A linear association of pC^* with increasing depth is consistent with the expectation of first order removal of particles with depth in porous media filtration (Iwasaki 1937).

In the absence of flocculation, the tube settler did not improve particle removal until the floc blanket exceeded

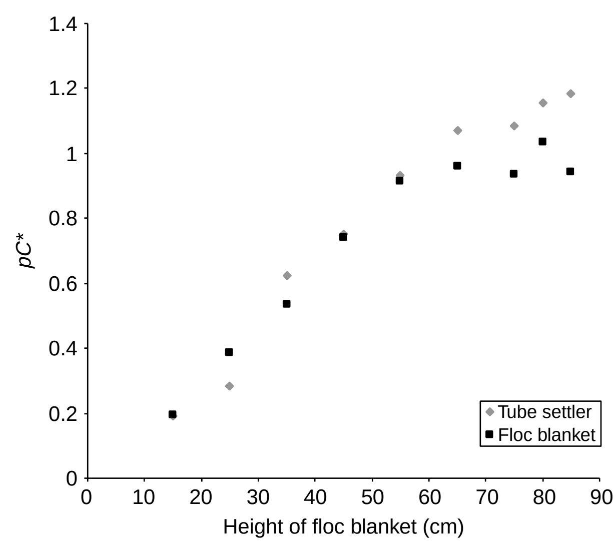

Figure 12 | Effect of floc blanket height without provision of flocculation on removal efficiency from both tube settler and floc blanket effluent.

55 cm (Figure 12). Since the energy dissipation rates in the floc blanket were sufficient to flocculate particles, the extent of flocculation would increase with residence time in the floc blanket, which increased as a function of blanket height. The data in Figure 12 indicates a floc blanket depth greater than 55 cm was required to create flocs large enough to have a terminal velocity that allowed them to be removed by the tube settler.

In pre-flocculated water, increasing particle removal in tube settler effluent was observed with increasing floc blanket depth up to a depth of 45 cm. However, particle removal within the floc blanket clarifier was relatively constant (Figure 13).

High efficiency flocculation was utilized in this study with a pC^* of approximately 0.7 or 80% removal (at 0 cm depth) before floc blanket. At 0 cm depth, the tube settler had a pC^* of 1.3, indicating that the tube settler was essential in improving performance. As floc blanket height increased with depth, it appears that particle removal mechanisms in the floc blanket were aiding in removing small particles (less than 0.12 $\mathrm{mm\,s^{-1}}$ terminal settling velocity) because tube settler performance continued to improve linearly with floc blanket depth up to a depth of 45 cm while floc blanket performance (i.e. particle removal by the floc blanket) varied by 0.5 pC^* units over 0 to 75 cm with a pC^* of 0.7 at 0 cm to a pC^* of 1.0 at 75 cm.

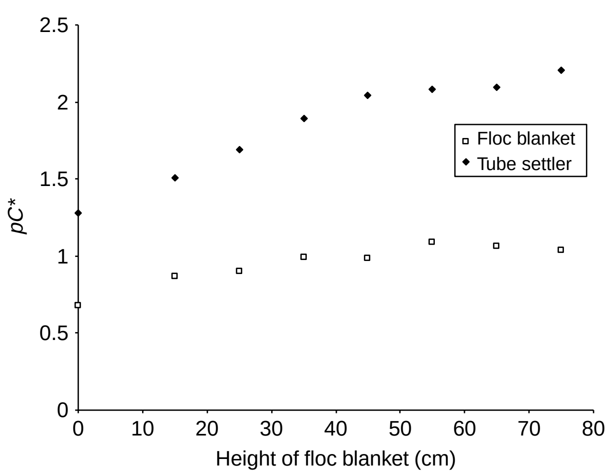

Figure 13 | Effect of floc blanket height on removal efficiency from both tube settler and floc blanket effluent for flocculation conditions in the flocculator of $G = 50\,\mathrm{s^{-1}}$ and $G\theta = 11{,}500$.

CONCLUSIONS

Optimal particle removal was obtained at an upflow velocity of 1.2 $\mathrm{mm\,s^{-1}}$ for all turbidities tested except for the case of high influent turbidity (500 NTU) that had an optimal upflow velocity of approximately 0.8 $\mathrm{mm\,s^{-1}}$. Control of upflow velocity was important to keep the bed of particles suspended in a floc blanket. At higher than optimal upflow velocities the decreased hydraulic residence time in the floc blanket would be expected to result in poorer filtration and flocculation. At lower than optimal upflow velocities, some particles settled and created channelling of the influent flow through the settled sludge. This channelling acted to decrease particle removal. At very low upflow velocities (0.4 $\mathrm{mm\,s^{-1}}$) there was no fluidized bed.

The provision of flocculation before floc blanket formation significantly enhanced performance of the floc blanket in removing particles. Increasing the energy dissipation rate in the flocculator could improve floc blanket performance; however because $G\theta$ was not varied while holding G constant, the effects of changes in $G\theta$ on floc blanket performance remain unclear. Increasing alum dose improved performance up to a point and then had no additional beneficial effect. The depth of floc blanket that was necessary to achieve minimum effluent particle concentration decreased as the extent of flocculation prior to the floc blanket increased. The minimum effluent particle concentration developed by a floc blanket may be limited by colloid production from floc break up caused by floc collisions. In the absence of flocculation prior to the upflow column, the tube settlers did not improve particle removal until the floc blanket was sufficiently deep that raw water colloids grew to have a terminal velocity that exceeded the tube settler capture velocity.

The results also show that lamellar settlers installed above a floc blanket can significantly improve particle removal efficiency. While turbidities of less than 1 NTU were achieved in the study, EPA standards for drinking water require an average effluent turbidity of 0.3 NTU or less. Thus, additional water treatment processes after sedimentation such as filtration and/or disinfection would be necessary to ensure that the EPA drinking water standard was met and ensure microbial safety.

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