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THESIS

EVALUATION OF COEFFICIENTS RELATED TO FLOC STRENGTH IN MULTILAYER FLOATING PLASTIC MEDIA FLOCCULATOR

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The performance of a multilayer floating-media flocculator using different bead sizes such as 3-mm, 6-mm and 10-mm was investigated in terms of large-floc formation and low-headloss development. The relationship between the maximum floc size (d_S) produced from flocculator and velocity gradient (G) was proposed with introducing the coefficients related to floc strength such as C_S and n. From the experimental results, the following conclusion were obtained. The dosages of coagulant, polyaluminium chloride (PACl) at 12.5%, 25%, 50%, 100 % and 400% of optimum dosage (10 mg/L) obtained from jar test under different hydraulic rates of 2.5 m^3/m^2-h, 5 m^3/m^2-h and 10 m^3/m^2-h were used to investigate the performance of this system. For an controlled experiment of 80-NTU influent turbidity, the optimum hydraulic rate and PACl dose were 2.5 m^3/m^2-h and 2.5 mg/L, the highest turbidity removal of 95.2%, the maximum floc size of 393 μm and the lowest headloss development of 10 mm were achieved in this optimum condition. The multilayer floating media took an advantage over the single media such as lower headloss development allowing fine floc to penetrate deeper, more area of media utilized, better turbidity control and the bigger floc formed by obtaining tapered flocculation. The results from mathematical modeling showed that the increase in velocity gradient (G) caused the decrease in maximum floc size (d_S). An empirical equation of single floating-plastic media could be written as $d_S = 19{,}798\ G^{-1.04}$ for the controlled experiment of 80-NTU influent turbidity, 2.5-mg/L PACl dose and 2.5-m^3/m^2-h hydraulic rate. Moreover, a simplified equation of d_S from the multilayer floating-media flocculator was also obtained as $d_{S,N} = 19{,}798 * R * \sum_{i=1}^{N} G^{-1.04}$; where R was a correcting factor that had values between 0.3 to 0.5 under the same controlled condition with the single media experiment.

H. Sasiwimol | Monthon Thanuttamvong | 24 / 03 / 2549

Student's signature | Thesis Advisor's signature

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Sasiwimol Hoontrakul
March 2006

TABLE OF CONTENTS

TABLE OF CONTENTS (cont'd)

LIST OF TABLES

LIST OF TABLES (cont'd)

LIST OF TABLES (cont'd)

LIST OF FIGURES

LIST OF FIGURES (cont'd)

LIST OF FIGURES (cont'd)

LIST OF FIGURES (cont'd)

LIST OF ABBREVIATIONS

Tb	=	Turbidity
NTU	=	Nephelometric turbidity unit
Δh	=	Headloss across bed depth (m)
C_S , n	=	Coefficients related to floc strength
d_S	=	Steady state maximum floc size (µm)
G	=	Velocity gradient (s^{-1})
g	=	Gravitational acceleration (m/s^2)
ν	=	Kinematical viscosity (m^2/s)
f	=	Porosity at time t, dimensionless
f_0	=	Initial porosity (dimensionless)
ΔL_L	=	Expanded depth (m)
θ	=	Hydraulic detention time in bed (s).
K	=	Kozeny's constant (dimensionless)
β'	=	head loss coefficient (dimensionless)
S_1	=	shape factor of particles (dimensionless)
S_2	=	shape factor of filter grains (dimensionless)
N_f	=	total number of floc retained in an unit area and depth ΔL of filter bed (cm^{-3})
N_c	=	total number of filter grains in an unit area and depth ΔL of filter bed (cm^{-3})
f	=	porosity (dimensionless)
d_c	=	diameter of collector (mm)
d_p	=	diameter of particle (µm)
v	=	hydraulic rate (m^3/m^2-h).

EVALUATION OF COEFFICIENTS RELATED TO FLOC STRENGTH IN MULTILAYER FLOATING PLASTIC MEDIA FLOCCULATOR

INTRODUCTION

In conventional water treatment systems, coagulation and flocculation are usually followed by sedimentation and filtration for elimination the fine suspended solids and colloidal solids in water. However, the system requires facilities that involve the high cost of construction, operation and maintenance. Consequently, the development of water treatment process requires compact and less energy consumption system whereas the system performance is comparable with the conventional processes. This aims to the new improvement on buoyant or floating plastic media flocculator.

Floating plastic media is a hydraulic flocculator that induces floc formation by using continuous flow of coagulated water through the porous of media. In the floating plastic media system, some flocs are retained in the pores of the media, decreasing void and promoting more contact between small particles and subsequent flow water. (Schulz *et al*., 1994). The advantages of floating plastic media are high efficiency to eliminate turbidity, producing uniform microfloc, easy to operate, small area using and low cost (Ngo and Vigneswaran, 1995a, 1995b; Visvanathan *et al*., 1996). The effectiveness of flocculation is evaluated in term of maximum floc size. Higher velocity gradient accelerates more opportunity for collisions resulting in rapid aggregation and floc formation. However, if velocity gradient is too vigorous, then the shear force will cause break-up of larger flocs and will limit the maximum floc size. Therefore, the flocculator should be designed to provide for tapered flocculation or subjected to decrease velocity gradient. The tapered flocculation is achieved by grading the bed of different sizes (from small to large size) which refer to multilayer floating plastic media.

The study can be separated into 2 main-parts such as the experimental methodology and the mathematical modeling. For the experimental methodology, the performance of a multilayer floating media flocculator was investigated in terms of large-floc formation and low-headloss development. For the mathematical modeling, the relationship between the maximum floc size (d_S) in the multilayer floating media and the velocity gradient (G) was estimated by introducing some coefficients related to floc strength such as C_S and n.

Objective

1. The performance of a floating plastic media flocculator was investigated in terms of large-floc formation and low-headloss development. As well as, the floc sizes produced from a single-medium layer and multi- (dual- and triple-) media layers using different floating-plastic media sizes were compared.

2. The coefficients related to floc strength of the flocs produced from the floating plastic-media flocculator were evaluated under different coagulant dosages of polyaluminium chloride.

Scope of the Study

1. The investigation of performance in floating plastic media was done in terms of large-floc formation and low-headloss development. The experiment was conducted in a bench-scale unit at the environmental engineering laboratory, Kasetsart University. The experimental parameters consist of floc size, turbidity, pH, hydraulic rate and head loss development. The comparison between the maximum floc size (d_S) and velocity gradient (G) produced from the single-medium layer and the multi- (dual- and triple-) media layers using different sizes of the floating-plastic media such as 3 mm, 6 mm and 10 mm in bead diameter was examined.

2. The coefficients related to floc strength, such as C_S and n, in the floating-plastic media flocculator were determined by using polyaluminium chloride (PACl) as the coagulant. The dosages of PACl were varied in the range of 1.25 to 40 mg/L. The coefficients related to floc strength was obtained by linearization curve of the natural logarithm of maximum floc size (d_S) against the natural logarithm of velocity gradient (G) in which the intercepting value on y-axis and the value of curve slope could be defined as natural logarithm of C_S (ln C_S) and n, respectively.

LITERATURE REVIEWS

Colloids Theory

The turbidity or dispersed particles range from about 0.01 to 100 μm. This fraction is difficult to settle. Their settling times are very slow. The behavior of colloids in water is strongly influenced by their electrokinetic charge. In general, each colloidal particle carries negative charge. This similar charge causes nearby particles to repel each other and prevents effective aggregation and flocculation. It results in charged colloids remain in suspension. The best way to gather colloids together is destabilization by forming small groups, then larger aggregates visible floc particles which settle rapidly and filter easily.

1. Electrical Double Layer Theory

The double layer model explains the ionic surrounding a charged colloid and explains how the repulsive forces are set up around a colloid. Figure1 illustrates the colloidal state. A negative colloid attracts some of the positive ions in the bulk solution to form a compact layer around the surface of the colloid, known as the Stern layer or Fixed layer. Not only additional positive ions are attracted by the negative colloid, but also repelled by the Stern layer as well as by other positive charged ions that try to get close to the negative charged colloid. This constant attraction-repulsion force results in the formation of a diffuse layer surrounding the colloid and the Stern layer.

The diffuse layer is a charged atmosphere surrounding the colloid. The compact positively charged ions in the Stern layer and the charged atmosphere in the diffuse layer are referred to as the double layers. The charge is a maximum at the colloid surface and decreases with distance from the surface. The thickness of this layer depends on type and concentration of ions in bulk solution.

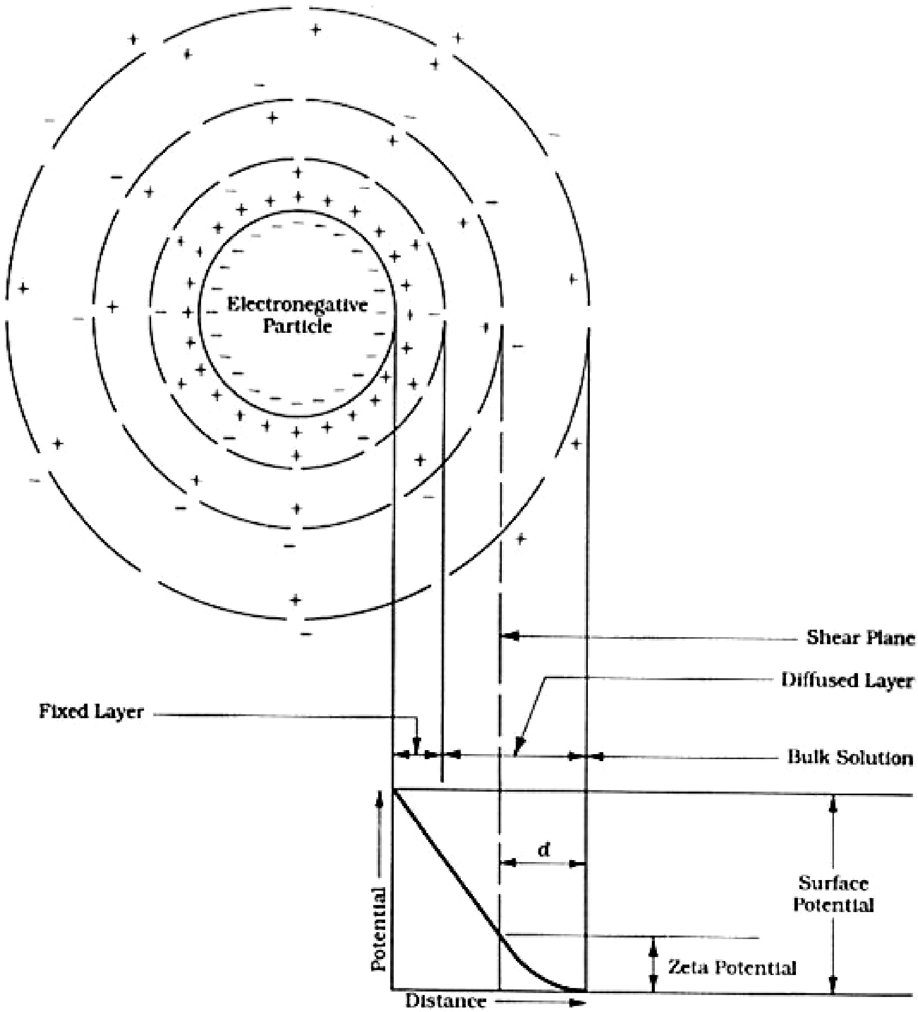


Figure 1 A negative colloidal particle with its electrostatic field

Source: Reynolds and Richards (1996)

2. Zeta Potential

The Stern layer is considered to be rigidly attached to the colloid, while the diffuse layer is a dynamic layer of charged particles. The Nernst Potential is the measurement of voltage in the diffuse layer. The maximum potential at the Stern layer declines exponentially through the diffuse layer. The zeta potential is the electrical potential representing the difference in voltage between the surface of the diffuse layer and the bulk solution. In the other word, it represents the strength of the repulsion between colloid particles and the distance which must be overcome to bring the particles together. The zeta potential can be calculated from measurements of measurements of particle movement within an electrical field. Consequently, the zeta potential is defined by the following equation.

$$\zeta = \frac{4\pi q d}{D} \qquad (1)$$

where; ζ = zeta potential

q = charge per unit area

d = thickness of the layer surrounding the shear surface through which the charge is effective, as shown in Figure 1

D = dielectric constant of the liquid

The destabilization of colloids is accomplished by the reduction of the zeta potential with coagulants such as alum, ferric chloride, polyaluminium chloride and/or cationic polymers. After the charge is reduced or eliminated, no repulsive forces exist. The gentle agitation in a flocculation process causes successful colloid collisions.

Coagulation

Coagulation (Destabilization) is the physical-chemical change that occurs between the soluble coagulant and the alkalinity in water to form precipitated or incipient floc. Coagulation includes feeding one or more chemicals to water and rapid mixing to disperse the chemicals. During mixing, or thereafter, chemical reactions occur, resulting in destabilization of colloidal and fine suspended solids and initial aggregation of destabilized particle (Cheremisinoff, 1995). Destabilization can be occurred by four processes. (Ravina and Moramarco, 1993).

1. Double layer compression

Double layer compression involves the addition of ionic compound to water. The change in ionic concentration compresses the double layer around the colloid. This mechanism is often called salting out.

2. Charge neutralization

Charge neutralization refers to the adsorption of a positively charged coagulant (such as alum) on the surface of the colloid. This positive charge neutralizes the negative charge of the colloid, resulting in a near zero net charge. Charge neutralization can be controlled by using zeta potential. This is important because overdosing can reverse the charge on the colloid, and redisperse it as a positive colloid, resulting in a poor flocculation.

3. Interparticulate bridging

Bridging occurs when long-chain polymers which carry negative charges attach to colloids, capturing and binding them together. Bridging is often used in conjunction with charge neutralization to form fast settleable floc. For the example, alum (low molecular weight cationic polymer) is first added under rapid mixing conditions to lower the charge and allow microflocs to form. Then a small amount of high molecular weight anionic polymer is added to bridge between the microfloc.

4. Colloid enmeshment

Colloid enmeshment refers to the adding excessive doses of coagulants, usually aluminum or iron salts which precipitate as insoluble metallic hydroxides, $Al(OH)_3$ or $Fe(OH)_3$. The negative colloids are swept from water by enmeshment in the settling hydrous oxide floc. This mechanism is often called sweep coagulation.

Coagulant

The coagulant can be separated into main 3 classes.

1. **Aluminium salts** such as

   Aluminium sulfate or alum: $Al_2(SO_4)_3.14.3H_2O$

   Ammonia alum: $Al_2(SO_4)_3(NH4)_2 SO_4.24H_2O$

   Potash alum: $Al_2(SO_4)_3K_2 SO_4.24H_2O$

2. **Iron salts** such as

   Copperas: $FeSO_4.7H_2O$

   Chlorinated copperas: $FeSO_4.7H_2O + Cl_2$

   Ferric chloride: $FeCl_3$

   Ferrifloc: $Fe_2(SO_4)_3$

3. **Others** such as

   Sodium aluminate: $NaAlO_2$

   Polyaluminium chloride: PACl

The differential chemicals may be used in coagulation depending on the characteristic of water being treated. In some water, the combination of two or more chemicals is better than one chemical alone. It is usually necessary to perform coagulation tests (jar test) in laboratory to decide which chemicals should be used.

Chiemchaisri *et al*., (2003) reported that the appropriate filtration rate of using combined floating plastic media (polypropylene) with sand for surface water treatment was 5 m^3/m^2-h. By comparison between PACl, alum and $FeCl_3$. Polyaluminium chloride was found to be the best coagulant which achieved the average suspended solids removal efficiency and average turbidity removal efficiency of 95.5% and 96.3%, respectively.

Polyaluminium Chloride

Polyaluminium chloride is a synthetic polymer that dissolves in water. It reacts to form insoluble aluminum poly-hydroxides which precipitate in bigger volumetric floc. Polyaluminium chloride can be used as a coagulant for all types of water treatment such as drinking water, industrial wastewater, urban wastewater (ENCO Engineering, 2003).

The advantages of PACl are composed of lower dosage requirement, no requirement for any neutralizing agent (i.e. soda or lime), shorter flocculation time, smaller amount of sludge, reduced number of backwashing steps, higher quality of the treated water, forming quickly settle flocs, and wide range of pH variation.

Flocculation

Flocculation refers to the gentle agitation of treated water for a period of time. The mechanism occurring in this step is the collision of the small floc particles with each other and with the other suspended particles in water. This occurrence causes them stick together or agglomerates and grows into large floc masses and readily settleable masses. (Cheremisinoff, 1995)

Three are three physical processes act to transport particles and increase particle-particle interaction, enhancing the likelihood of coagulation and flocculation: perikinetic flocculation (Brownian diffusion), orthokinetic flocculation (fluid shear), and differential settling. (Blazier, 2003). The diagram of these processes is shown in Figure 2.

1. Perikinetic flocculation

Perikinetic flocculation is the result of collisions of the small particles due to Brownian motion. This motion induces by temperature of the water. This process occurs when the diameter of the particles is less than 1 micron, so it does not help to grow the larger floc. This results in a "micro-floc"

2. Orthokinetic flocculation

Orthokinetic flocculation is the growth of the particles due to fluid motion (agitation). This process produces the bulky separable floc needed for clarification by sedimentation or filtration.

3. Differential settling

Differential settling occurs when particles settle due to gravity and collide with other particles forming flocs during vertical transport.

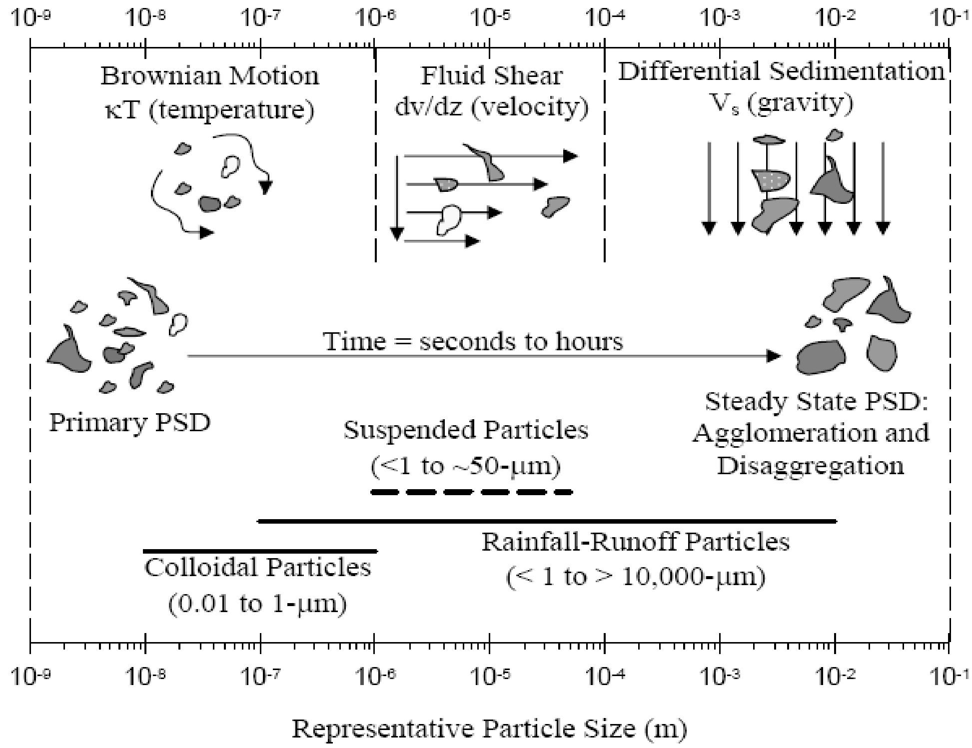


Figure 2 Conceptual schematic of the sub-processes controlling particle aggregation, the size spectrum for naturally occurring rainfall-runoff particles

Source: Blazier (2003)

The agitation in flocculation can be induced by mechanical flocculators such as paddle, propeller, turbine and etc. or hydraulic flocculators such as baffle channel, coarse media and etc. Schulz *et al*., (1994) evaluated the new development of coarse media flocculator that used floating or buoyant plastic media in laboratory and field. The study reported that two-stage buoyant media flocculator took advantages such as effective treatment at higher loading rate and shorter residence time than mechanical flocculator.

Principle of Floating Plastic Media

In conventional water treatment system, coagulation and flocculation are usually followed by sedimentation and filtration for elimination the fine suspended solids and colloidal solids in water and disinfection for killing pathogens. However, the system requires facilities that involve the high cost of construction, operation and maintenance. Consequently, the development of water treatment process requires compact and less energy consumption system whereas the system performance is comparable with the conventional processes. Therefore, this research is related to the new development of compact and economic process, or referred to floating plastic media flocculator.

Floating plastic media flocculator is developed from contact-flocculation filtration, a process whereby coagulant is added directly to the raw water immediately. After that both of flocculation and filtration are occur within filter bed itself (Kawamura, 1991). The diagram of contact-flocculation filtration is shown Figure 3. The typical media filter using in contact-flocculation filtration is composed of sand, anthracite, gravel and etc. The drawbacks of these heavier media such as high energy consuming for backwashing, high clogging, intermixing of gain after backwashing, and high headloss development (Lager *et al*., 1977) lead to the new improvement on buoyant or floating plastic media by many researchers (Ngo and Vigneswaran, 1995a, 1995b; Schulz *et al*., 1994; Visvanathan *et al*., 1996).

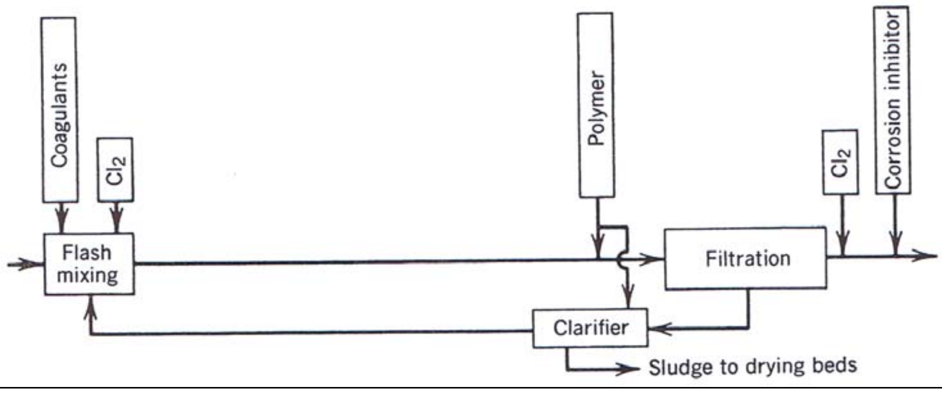


Figure 3 Contact flocculation-filtration process

Source: Kawamura (1991)

Numerous floating plastic media flocculators have been tried to use in water and wastewater treatment. The experiment (using polypropylene bead of depth 16-40 cm) produced the uniform microfloc (26-40 μm), low headloss development (3 cm in 4 hours) and increased removal efficiency when operating at higher media depth and lower filtration rate (Ngo and Vigneswaran, 1995a). The result from the experiment using combined system between floating plastic media and coarse sand filter unit compared with single floating plastic media showed that combined system increased removal efficiency (more than 87% and 94% of NH_3-N and total-P removal, respectively), especially at low filtration rate: 5 m^3/m^2-h (Ngo and Vigneswaran, 1995b).

In addition, Visvanathan *et al*., (1996) did experiments with coarse polypropylene and fine polystyrene as dual floating media filter. The result from the study showed that the advantages of dual floating media filter was higher turbidity removal per unit headloss than sand filter, lower headloss development, higher retention capacity, solving problem of intermixing and elimination the need of elaborate underdrain system causing the reduction of capital, operation and maintenance costs.

Floating plastic media is a hydraulic flocculator that induces floc formation by using continuous flow of coagulated water through the porous of media and separating floc and particle by filter bed. In floating plastic media, floc is retained in the porosity of the media, decreasing void and promoting more contact between small particle and subsequent flow water. Tapered flocculation is achieved by grading the bed of different size or changing in cross-section area. There are three major processes involving in the floating plastic media: coagulation, flocculation and filtration (Schulz *et al*., 1994).

Rate of Flocculation

In general, the rate of flocculation is controlled by two factors.

1. Concentration of particles (both free colloids and flocs)

A greater number of particles provide more opportunity for collisions occurrence between colloids themselves and between floc and colloids. This increases the rate of capture.

2. Velocity gradient

The velocity gradient (G) is a measure of the mixing energy that occurs during both the rapid mix and the slow mix. This value explains as the amount of velocity change per unit of distance of the change occurring. In hydraulic flocculator, velocity gradient is dictated by headloss which occurs by fluid shear as water flow through a tortuous path around each grains of media. This results in small eddies that encourage the interparticle collision. Headloss is function of volume of floc retained in bed, cross-section area of bed, size of media and rate of flow. (Schulz *et al*., 1994)

The higher velocity gradient provides more opportunity for particle collisions, resulting in aggregation and floc formation. However, the shear forces from too high velocity gradient can break up larger floc and limit the maximum floc size. The principle of floc break-up consisted of (1) surface erosion and (2) fracture. (Figure 4) The simultaneous processes of aggregation and breakup resulted in the maximum floc size, d_S (Argaman and Kaufman, 1970; Parker *et al*., 1972):

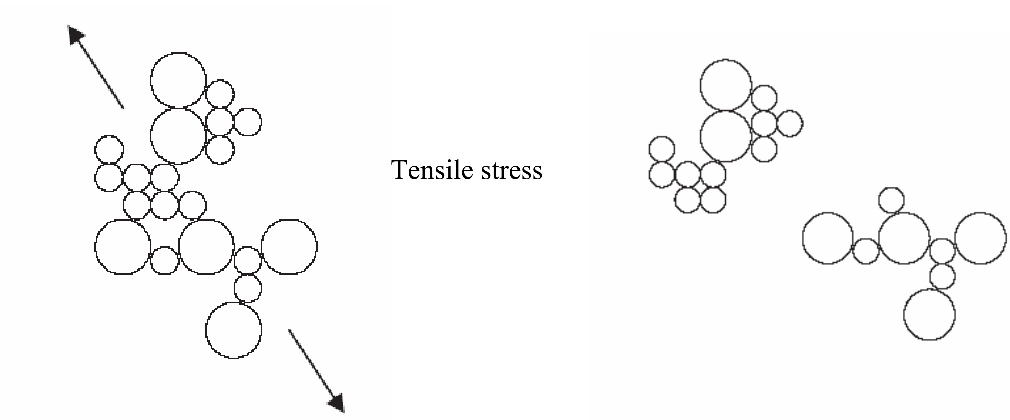
$$d_S = C_S G^{-n} \qquad (2)$$

where; d_S = maximum floc size (µm)

G = velocity gradient (s^{-1})

C_S, n = coefficients related to floc strength

1. Large scale fragmentation.



2. Surface erosion.

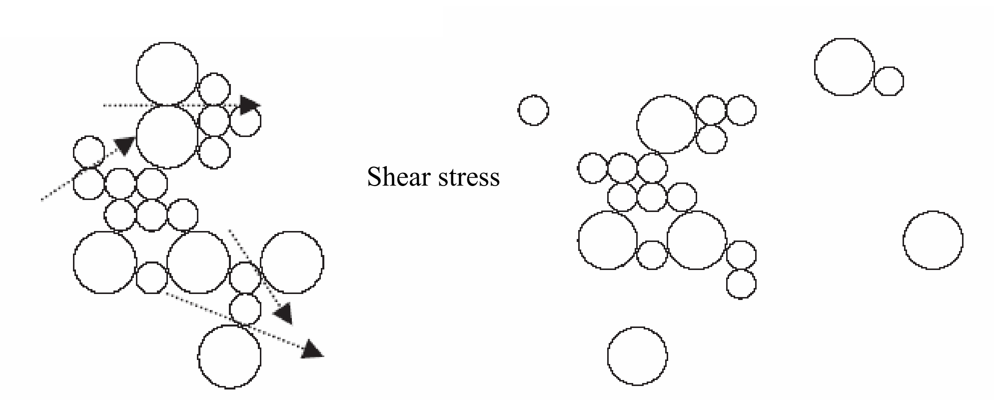


Figure 4 Two proposed mechanisms for the breakage of floc under different shear conditions. Source: Jarvis *et al.* (2005)

Linearization of the equation (2) allows values of n (slope) and ln C_S (y-axis intercept) to be found from a ln–ln plot of the maximum floc size (d_S) against the velocity gradient (G).

$$\ln d_S = \ln C_S - n \ln G \tag{3}$$

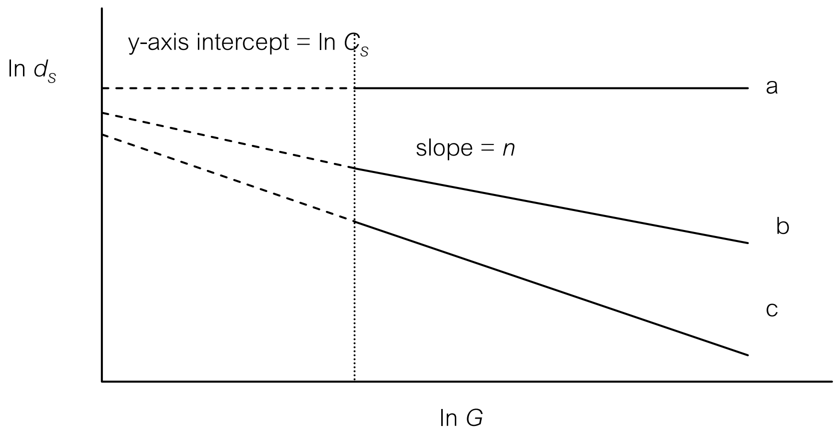


Figure 5 Relationship between the change in particle size and an increase in velocity gradient for three types of floc. Floc (a) is resistant to breakage, floc (b) is thought to break due to large scale fragmentation and floc (c) is thought to break by surface erosion

Source: Jarvis *et al*. (2005)

There has been wide variation between different studies in C_S within specific experimental systems. The value of n remains relatively constant. Therefore, the value of n is a useful value for comparing floc strength and break-up (Jarvis *et al*., 2005).

Figure5 shows the three examples of different floc formed and break-up. For line (a) the slope of the line is zero and floc size is independent of the applied shear rate or velocity gradient. The floc do not break-up when exposure to shear and as must be considered strong floc. If the slope of the line is shallow as in line (b) then these floc are better able to resist shear than the floc in line (c). Therefore, floc (b) should be considered stronger than floc (c) as the maximum floc size does not decrease so rapidly. In general, the value of n indicate how floc will respond to subsequent increases in shear rate (Jarvis *et al*., 2005)

Table 1 Value of the floc strength constants and co-efficient obtained from shear-based techniques

Type of floc	Coagulant type and dose	The co-efficient related to Floc strength, log C_S	Floc strength constant, n	Reference
Alum sludge	Cationic polymer (PL-320) 0-30 mg/L	2.4-5.9	N/A	Wu *et al* ., (2003)
Alumino-humic in low alkalinity and high colour water	Al-based coagulant			Bache and Rasool (2001)
	2.4 mg/L as Al	3.8	0.61	
	2.7 mg/L as Al	3.4	0.63	
	4.7 mg/L as Al	3.6	0.57	
	5.4 mg/L as Al	3.6	0.52	
	2.5 mg/L as Al^+	3.8	0.44	
	0.1 mg/L polymer	4.0	0.64	
	3.7 mg/L as Al^+ 0.1 mgL 1 polymer Al-based coagulant	4.1	0.81	
Alumino-kaolin in deionised water	Aluminium sulphate			Francois (1987)
	4.02 mg/L as Al		0.44	
	4.52 mg/L as Al		0.48	
	5.02 mg/L as Al		0.61	
	5.52 mg/L as Al		0.50	
	6.02 mg/L as Al		0.43	

Source: Jarvis *et al*. (2005)

Mathematical Model Formulation of Flocculation

Velocity gradient

Ngo *et al*., (1996) did experiments with polypropylene bead as downflow floating medium filter at operating filtration rate 2, 5, 8 and 10.5 m^3/m^2-h. The filter bead was packed in column to depth of 10, 20 and 30 cm. The semi-empirical equation resulting from experiment was written as below:

$$d_f = 199.799\, t^{0.393} G^{-0.552} \quad (r = 0.945) \tag{4}$$

$$d_u = 130.45 G^{-0.394} \quad (r = -0.994) \tag{5}$$

where; d_f=diameter of floc in µm, t = time in second and d_u = ultimate floc diameter.

The equation (4) and (5) were formulated by base on the equation as shown below:

$$G = \sqrt{\frac{g \cdot \Delta h}{\nu \cdot f \cdot \theta}} \tag{6}$$

where; G = velocity gradient (s^{-1})

g = gravitational acceleration (m/s^2)

Δh = head loss across bed depth (m)

ν = kinematical viscosity (m^2/s)

f = porosity, dimensionless = $\frac{f_0 (L + \Delta L_L)}{L}$ (7)

f_0 = initial porosity (dimensionless)

ΔL_L = expanded depth (m)

θ = hydraulic detention time in bed (s).

Mechanisms of Solid Removal in Granular Medium-Depth Filter

Conventional filtration is the separation of solid particles from a liquid by passing through a medium, such as sand, anthracite coal, activated carbon and etc. After that filter retains the solid on its surface and allows the liquid to pass through.

Table 2 Principal mechanisms and phenomena contributing to removal of material with in granular medium-depth filter

Mechanism/phenomenon	Description
1. Straining	
a. Mechanical	Particles larger than the pore space of the filtering medium are strained out mechanically
b. Chance contact	Particles smaller than the pore space are trapped within the filter by chance contact
2. Sedimentation	Particles settle on the filtering medium within the filter
3. Impaction	Heavy Particles will not follow the flow streamlines
4. Interception	Many particles that move along in the streamline are removed when they come in contact with the surface of the filtering medium
5. Adhesion	Particles become attached to the surface of the filtering medium as they pass by. Because of the force of the flowing water, some material is shared away before it become firmly attached and is pushed deeper into the filter bed. As the bed becomes clogged, the surface shear force increases to a point at which no additional material can be removed. Some material may break through the bottom of the filter,

<u>Table 2</u> (Cont'd)

Mechanism/phenomenon	Description
5. Adhesion (cont'd)	causing the sudden appearance of turbidity in the effluent
6. Flocculation	Flocculation can occur within the interstices of the filter medium. The larger particles formed by the velocity gradients within the filter are then removed by one or more of the above removal mechanisms.
7. Chemical absorption a. Bonding b. Chemical interaction 8. Physical absorption a.Electrostatic forces b.Electrokinetic forces c.Van der waals forces	Once a particle has been brought in contact with the surface of the filtering medium or with other particles , either one of these mechanisms, chemical or physical absorption or bath, may be responsible for holding it there
9. Biological growth	Biological growth within the filter will reduce the pore volume and may enhance the removal of particles with any of the above removal mechanisms[1 through 5]

Source: Metcalf and Eddy (2003)

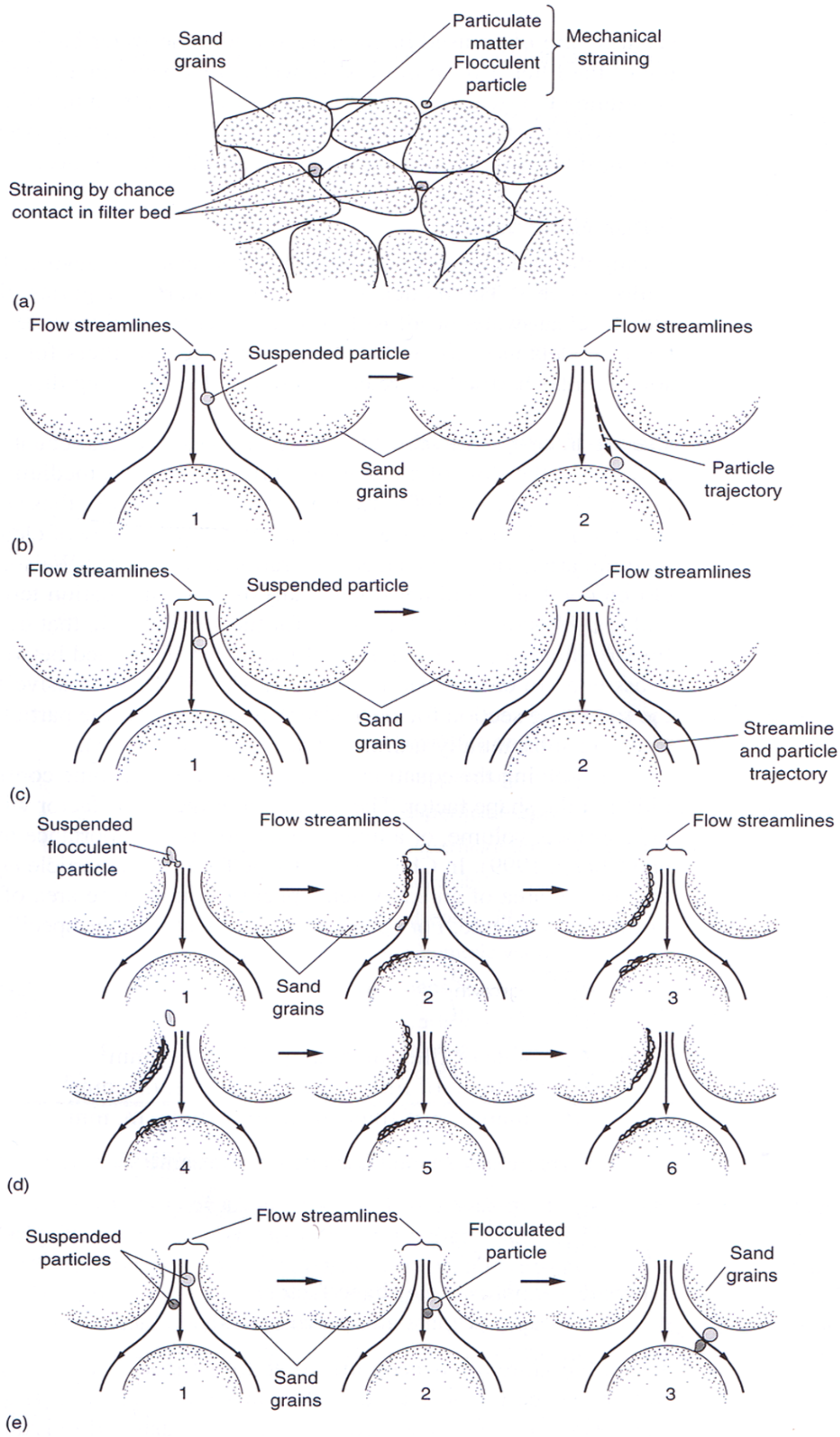


Figure 6 Removal of suspended particle matter with in a granular filter (a)by straining (b) by sedimentation or inertial impaction (c) by interception(d) by adhesion (e) by flocculation.

Source: Metcalf and Eddy (2003)

Direct Filtration and Contact-Flocculation Filtration

Direct filtration process refers to the filtration without sedimentation. In this process, coagulated water containing destabilized particle is directly fed through the filter bed. The agglomeration of particle to form visible floc occurs from the number of opportunities for collision of particle in porous media. After that floc is separated by attachment or adsorption to surface of filter grain. This mechanism defines as contact-flocculation filtration. (Culp, 1977)

Luttinger (1981) concluded that the direct filtration process required the pin point floc (small-dense floc) more than large floc (sweep floc). This strength floc was allowed to well penetrate into the deeper filter zone resulting in the full storage capabilities of filter grain and longer filter run. This manner corresponded to the finding of Kludpiban (2000). She studied the turbidity removal by using Floating plastic media process. The experiment used $FeCl_3$, Alum, PACl like coagulant at 20%, 40% and 60% of optimum dose obtained by Jar test. Polyalumimium chloride represented the best efficiency for both turbidities of 20 and 40 NTU at 20% of optimum dose obtained by Jar test. At the turbidity of 20 NTU, this dose achieved the short term and long term turbidity removal efficiency of 96.8% and 81.8%, respectively. At the turbidity of 40 NTU, this dose achieved the short term and long term turbidity removal efficiency of 97.7% and 94.6%, respectively.

Mathematical Model Formulation of Filtration

The importance parameters in bed filtration that mention in this experiment consists of filter performance and headloss development. These parameters can be calculated by the following equations.

The headloss equation (h_0) for clean bed has been developed based on Kozeny's equation.

$$\frac{h_0}{L} = K\frac{\mu}{\rho}\frac{v}{g}\frac{(1-f_0)^2}{f_0^3}\left[\frac{A_c}{V_c}\right]^2 \tag{8}$$

The change of porosity and surface area of media due to the accumulation of floc should be considered. Therefore, the headloss (h_f) of clogged bed can be written as below.

$$\frac{h_f}{L} = K\frac{\mu}{\rho}\frac{v}{g}\frac{(1-f_0)^2}{f_0^3}\frac{\left[A_c + A_p\right]^2}{\left[V_c + V_p\right]^2} \tag{9}$$

Substituting for area of collector and particle collector in unit volume of filter (A_c and A_p) and volume of collector and particle collector in unit volume of filter (V_c and V_p), obtains (O'Melia and Ali, 1978).

$$\frac{h_f}{L} = 36K\frac{\mu}{\rho}\frac{v}{g}\frac{1}{d_c^2}\frac{(1-f)^2}{f^3}\left[\frac{1+\beta'(N_p/N_c)(d_p/d_c)^2}{1+(N_p/N_c)(d_p/d_c)^3}\right]^2 \tag{10}$$

Considering the effect of shape factor of suspended particle (S_1) and filter media (S_2), equation (10) can be rewritten as (Vigneswaran and Change, 1986):

$$\frac{h_f}{L} = 36K\frac{\mu \upsilon_a (1-f)^2}{\rho_f g . f^3}\frac{1}{d_c^2}\left[\frac{S_2}{6}\right]^2\left[\frac{1+\beta'(S_2/S_1)^2(N_p d_p^2)/(N_c d_c^2)}{1+(S_2/S_1)^3(N_p d_p^3)/(N_c d_c^3)}\right]^2 \tag{11}$$

where; h_f = headloss (cm)

K = Kozeny's constant (dimensionless)

β' = head loss coefficient (dimensionless)

S_1 = shape factor of particles (dimensionless)

S_2 = shape factor of filter grains (dimensionless)

N_f = total number of floc retained in an unit area and depth ΔL of filter bed (cm^{-3})

N_c = total number of filter grains in an unit area and depth ΔL of filter bed (cm^{-3})

f = porosity (dimensionless)

d_c = diameter of collector (mm)

d_p = diameter of particle (μm)

v = hydraulic rate (m^3/m^2-h).

MATERIALS AND METHODS

Materials

1. Reactor - The acrylic clear reactor has 9 cm. in diameter and 150 cm. in length. Polypropylene beads with a diameter of about 3, 6 and 10 mm were used as the floating media in downflow flocculator.
2. 1000 L Raw water tank
3. Submerge pump capacity 100 L/min, Ogarmar
4. Constant head tank
5. Rapid mixing device
6. Peristaltic pump for feeding chemical, Masterflex, Model MP3, Evela
7. Flow meter
8. Piezometer
9. Jar test apparatus, Model PB-700TM, Phipps&Bird
10. Coagulant: polyaluminium chloride (PACl)
11. PH meter, Model 215, Denver Instrument
12. Turbidimeter, Model 2100 P, Hach
13. Kaolin clay 200 mesh
14. Glass ware for analysis

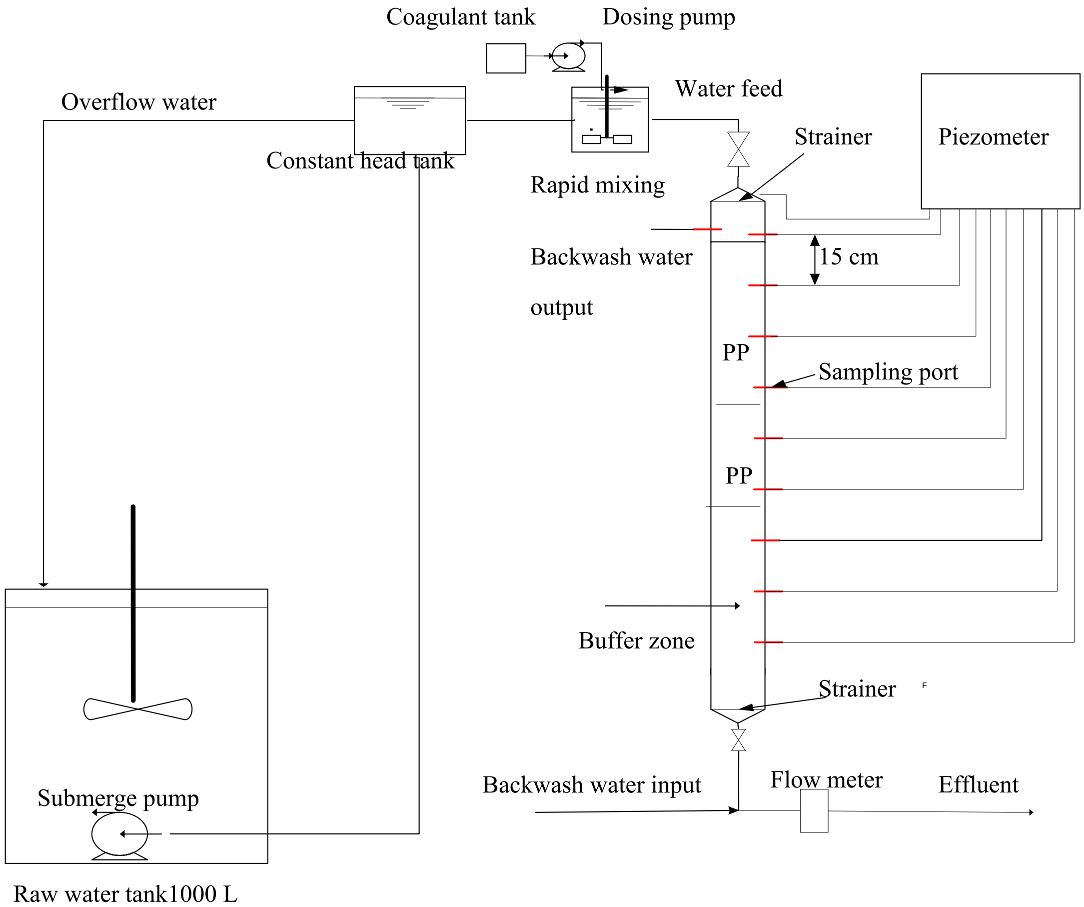


Figure 7 Experimental Setup

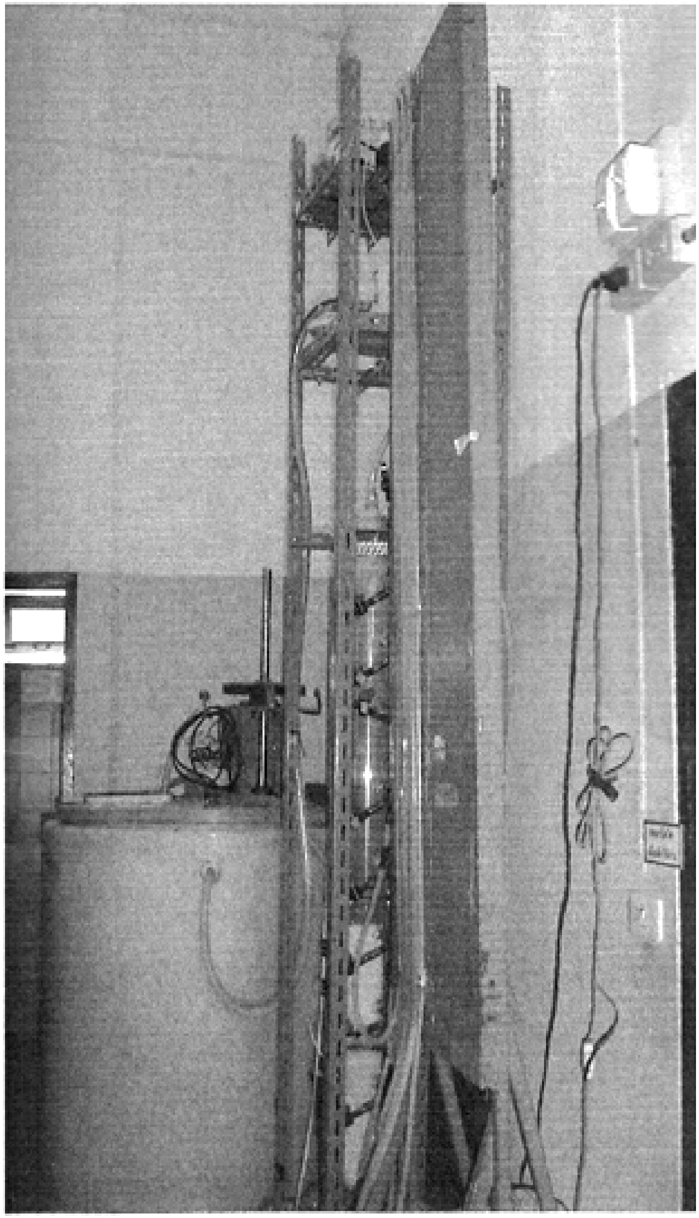


Figure 8 Experimental setup as bench-scale at Kasetsart University

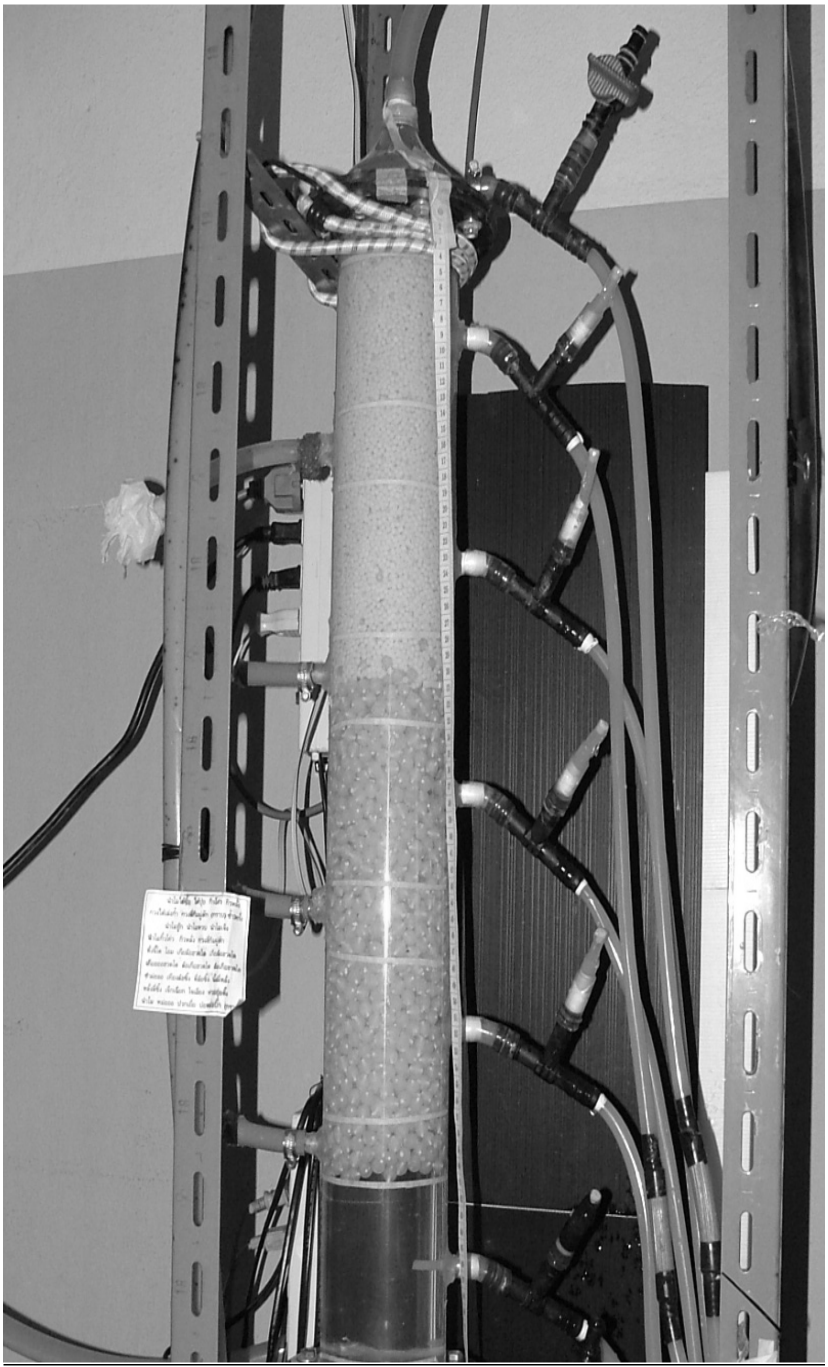


Figure 9 Floating plastic media flocculator column with 3-mm and 10-mm media sizes

Methods

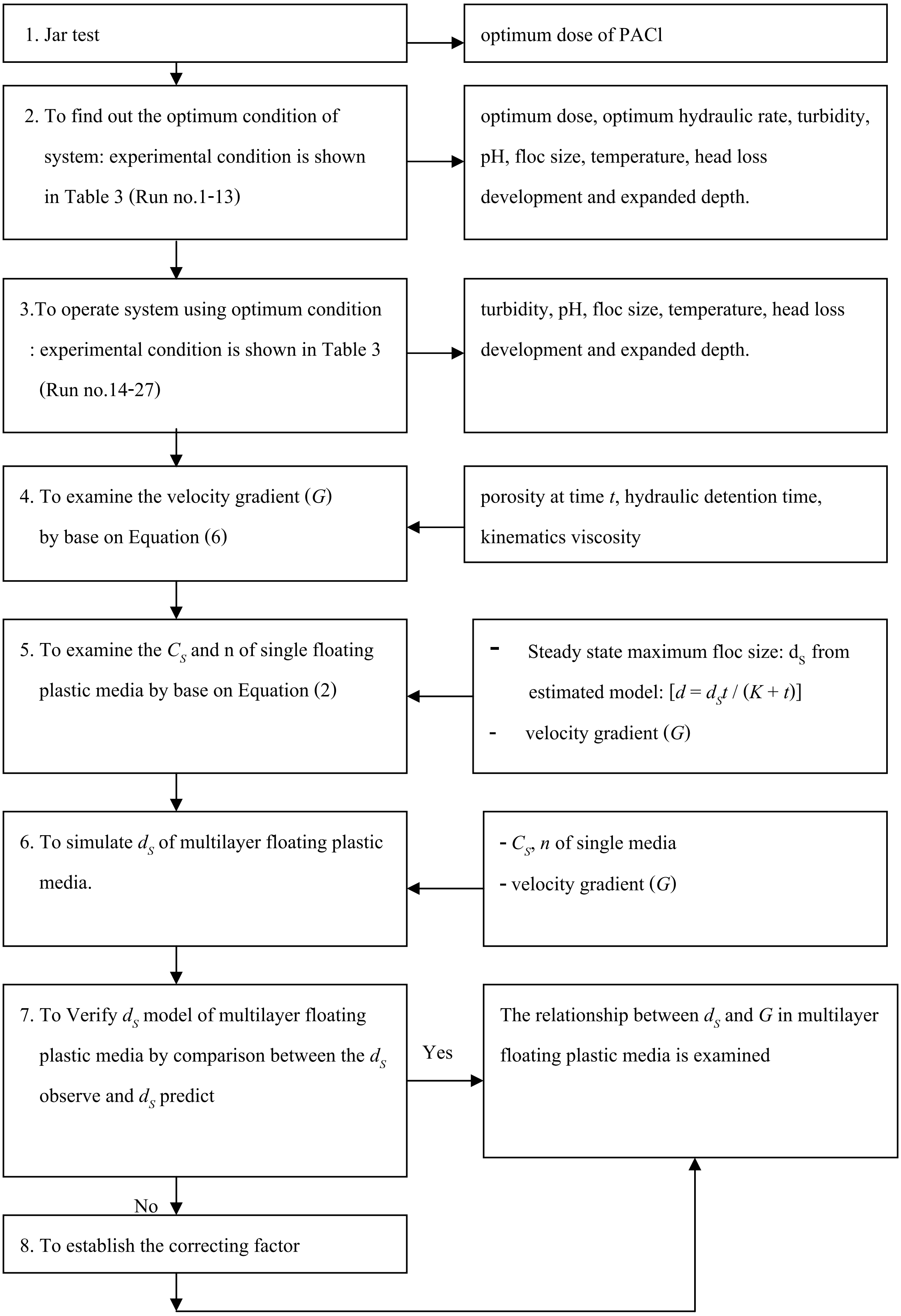


Figure 10 Experimental methodogy

1. <u>Jar test</u>

The optimum dose of coagulants: polyaluminium chloride (PACl) that used to eliminate turbidity was determined. The procedure was as follows.

1.1 The coagulant was added in beaker to give different concentrations, and the suspension was stirred rapidly (100 rpm) for 1 minute to ensure adequate mixing.

1.2 The rapid mixing was done following by slow stirring at calculated velocity gradient approximately 30 s^{-1} for 10 minutes to give opportunity for particle collisions and aggregate formation.

1.3 The suspension was then allowed to settle for 5 minutes, and the sample is drawn at depth of 1/3 from the water line to measure turbidity and pH.

1.4 The best coagulant at its optimum dosage that lead to the turbidity less than 7 NTU was selected.

1.5 The experiment was repeated at different calculated velocity gradient approximately 40 s^{-1}, 50 s^{-1} and 60 s^{-1}, respectively.

2. <u>Optimum condition of floating plastic media flocculator (Run no.1-13)</u>

2.1 Synthetic raw water using kaolin clay prepared in tap water at turbidity level of 80 NTU was used in the experiment.

2.2 Raw water was pump into constant head tank which continuously supplies water into the rapid mixing device.

2.3. The optimum dosage of PACl that determined from jar test was added into the feed line ahead of rapid mixing device (approximately one-second mixed). Polyalumimium chloride was fed by using a chemical dosing pump. Subsequently, coagulated water was continuously supplied into column.

2.4 The experimental system (Figure 6) was operated in short term run following the condition that shows in Table 3.

2.5 The water from outlet sampling port was sampled to analyze every 30 minutes in the first 3 hours and every 1 hour in the next 3 hours. The experimental parameters were composed of turbidity, pH, floc size, temperature.

2.6 The head loss development and expanded depth were recorded every 30 minutes during the first 3 hours and every 1 hour during subsequent 3 hours.

3. <u>Performance of floating plastic media flocculator (Run no.14-27)</u>

3.1 The floating media was changed following the condition that shows in Table 3.

3.2 The experiment was done by repeating the experiment no. 2.1 to 2.6. The optimum condition was used to operate system.

4. <u>Velocity gradient</u>

From the parameters that get from the experiment no. 2 and 3 (Run no.1-27), the velocity gradient (*G*) was calculated by base on model of Ngo. *et al.*, (1996) from

$$G = \sqrt{\frac{P}{\mu \cdot v_v}} \qquad (12)$$

where; $P = \rho g h Q$

$V_v = fV$

$\theta = V / Q$

$\nu = \mu / \rho$

Substituting above parameter in equation (12) yields:

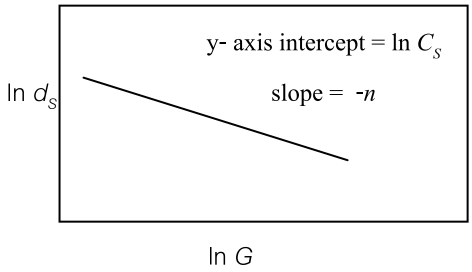
$$G = \sqrt{\frac{\rho \cdot g \cdot \Delta h \cdot Q}{\mu \cdot f \cdot V}} \qquad (13).$$

Finally, the equation corresponding to Equation (6) can be obtained as follow:

$$G = \sqrt{\frac{g \cdot \Delta h}{\nu \cdot f \cdot \theta}}$$

5. Coefficients related to floc strength in single floating media flocculator (Run no.14-27)

Linearization of the equation of Parker *et al*., (1972) allowed values of n and ln C_S to be found from a ln–ln plot of the maximum floc size (d_S) against the velocity gradient (G).



$$d_S = C_S \cdot G^{-n}$$

$$\ln d_S = \ln C_S - n \ln G$$

Figure 11 Relationship between velocity gradient (G) and the maximum floc size (d_S)

Velocity gradient (G) was calculated from the experiment no (6) and d_S was estimated by equation as shown below: (see Appendix Figure A)

$$d = d_S t \,/\, (K + t) \tag{14}$$

where; d = maximum floc size at time t (μm),

d_S = maximum floc size at steady state (μm)

K = time at $d = d_S/2$.

6. Prediction of maximum floc size in multilayer floating-plastic media flocculator

The d_S produced from the multilayer floating-plastic media flocculator were predicted as:

$$d_S = C_S * \sum_{i=1}^{N} G^{-1.04} \tag{15}$$

then, the observed (experimental) d_S and the predicted (calculated) d_S were compared. If the observed d_S did not correspond to the predicted d_S, the correcting factors would been established.

Table 3 Experimental Schedule

Run No.	Media Size (mm)	HydraulicRate ($m^3 / m^2 . hr$)	Coagulant dose (mg/L)	Analytical Parameter
1-3 (Single Media)	3	2.5	10 , 5 , 2.5	turbidity, pH, max. floc size, temperature, head loss development, expanded depth & velocity gradient.
4-8(Single Media)	3	5.0	40 ,10 , 5 , 2.5 ,1.25	
9-13(Single Media)	3	10.0	40 ,10 , 5 , 2.5 ,1.25	
14-15 (Single Media)	6	2.5	2.5	
16-17 (Single Media)	3	2.5	2.5	
18-19 (Single Media)	10	2.5	2.5	
20 (Dual Media)	6, 10	2.5	2.5	
21 (Dual Media)	6, 10	2.5	2.5	
22 (Dual Media)	3, 6	2.5	2.5	
23(Dual Media)	3, 6	2.5	2.5	
24 (Dual Media)	3,10	2.5	2.5	
25 (Dual Media)	3,10	2.5	2.5	
26(Multi Media)	3, 6, 10	2.5	2.5	
27(Multi Media)	3, 6, 10	2.5	2.5	

RESULTS AND DISCUSSION

The Performance of System

1. Jar test

The optimum dosage of polyaluminum chloride (PACl) was estimated using standard jar test procedure. Figure 12 illustrated the laboratory jar test results on raw water of turbidity 80 NTU. From Figure 12, the optimum dose of PACl were found to be 10 mg/l where the percent turbidity removal of 95, 95, 91 and 91 could be obtained at the velocity gradients of 30 s^{-1}, 40 s^{-1} ,50 s^{-1} and 60 s^{-1}, respectively.

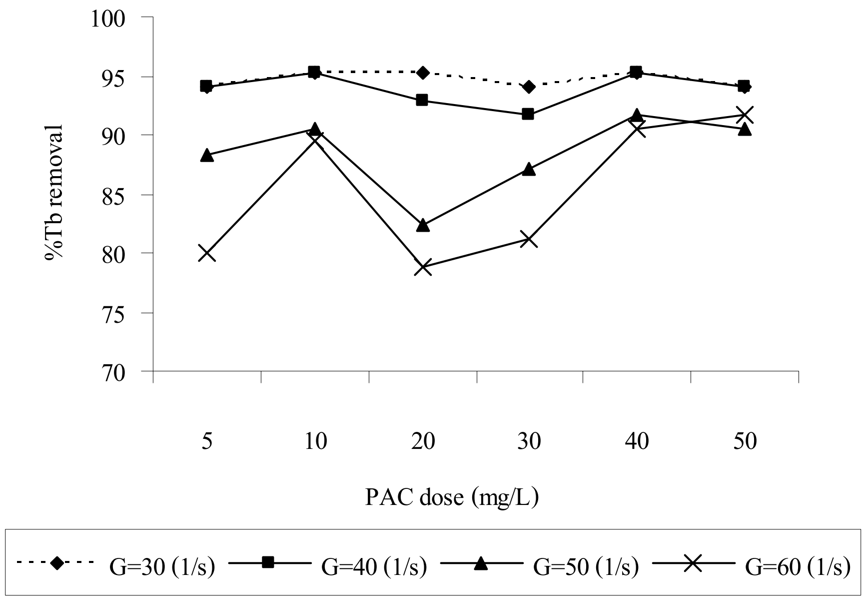


Figure 12 Effect of coagulant dose at different velocity gradients on turbidity removal

Table 4 summarizes the effect of PACl doses and velocity gradients on the average floc sizes. The polyalumimium chloride dose of 10 mg/l yielded good aggregation of floc where the average floc size of 101, 69, 62 and 58 µm could be obtained at the velocity gradients of 30 s^{-1}, 40 s^{-1}, 50 s^{-1} and 60 s^{-1}, respectively. It could be observed that the higher velocity gradient produced the smaller average floc size at the same coagulant dose.

Table 4 Average maximum floc size at different velocity gradients and PACl doses

PACl dose (mg/L)	Average maximum floc size (μm)			
	G = 30 s^{-1}	G = 40 s^{-1}	G = 50 s^{-1}	G = 60 s^{-1}
5	63	49	42	24
10	101	69	62	52
20	63	61	56	29
30	61	59	48	33
40	102	71	53	49
50	62	57	48	49

However, the flocculation in jar test usually required higher coagulant dosage than the flocculation in media (contact-flocculation) (Kludpiban, 2000). Moreover, the mechanism of flocculation in porous media is still unclear as well as the development of headloss in the media layer can occur dynamically. Consequently, the optimum dose from jar-test experiment could not be used directly for the operation of the floating-plastic media flocculator.

2. Optimum condition of floating-plastic media flocculator

This study was firstly done by applying floating media of polypropylene beads with a diameter of about 3 mm and a layer depth of 60 cm. The synthetic raw water using kaolin clay with an approximate turbidity of 80 NTU was prepared. The performance of floating media flocculator was examined using different doses of polyaluminum chloride at 12.5% (1.25 mg/L), 25% (2.5 mg/L), 50% (5 mg/L) , 100 % (10 mg/L) and 400% (40 mg/L) of the optimum dose obtained from jar test (10 mg/L). The system was operated at different hydraulic rates of 2.5, 5 and 10 m^3/m^2-h.

2.1 Effect of polyaluminium chloride dosage

2.1.1 Effect of PACl doses on turbidity removal and average maximum floc size

Figure 13 shows the system performance in term of turbidity removal at different PACl doses and the hydraulic rate of 2.5 m^3/m^2-h. From the results, the turbidity removal at PACl doses of 2.5 mg/L and 5 mg/L were not significant different and rather constant at a high value of 96.4% in the long-term operation, while the turbidity removal at PACl dose of 10 mg/L, corresponding the optimum dose obtained from jar test, was found to be a lower value of 87.9%.

The effects of different PACl doses at the hydraulic rates of 5 m^3/m^2-h and 10 m^3/m^2-h on turbidity removal were found in Figure14 and Figure15, respectively. In Figure14, the high turbidity removal, which was more than 85%, at PACl doses of 40 mg/L, 10 mg/L, 5 mg/L, 2.5 mg/L and 1.25 mg/L were deteriorated after 60, 90, 150, 240 and 600 minutes of operating time, respectively. It indicated that the higher PACl dose performed faster breakthrough of turbidity. The same results were also found in Figure15. The quality of effluent water were deteriorated over 30, 60, 60, 90 and 150 minutes of operating time at PACl doses of 40 mg/L, 10 mg/L, 5 mg/L, 2.5 mg/L and 1.25 mg/L, respectively.

From Figures 13-15, it was observed that application of PACl dose at 2.5 mg/L could produce a good effluent in term of low turbidity (high turbidity removal) for any hydraulic rate.

Table 5 summarized the experimental results obtained at different hydraulic rates and PACl doses. From Table 5, PACl dose of 2.5 mg/L provided the highest average turbidity removal percent of 95.2, 91.4 and 79.8 at hydraulic rates of 2.5, 5 and 10 m^3/m^2-h, respectively. The maximum average floc produced from floating media flocculator at 2.5 mg/L PACl also yielded the biggest size of 393, 340, 255 at hydraulic rates of 2.5, 5 and 10 m^3/m^2-h. It should be note that the optimum dose of system was 2.5 mg/L of PACl.

From the experiment, the optimum coagulant dose in floating media column was 2.5 mg/L while the optimum coagulant dose in jar test was 10 mg/L. As mention before, the flocculation in floating media column required lower coagulant dosage than the flocculation in jar test. It was because that the floating-media column performed similar to a contact flocculator which promoted the change in velocity gradient along the flow direction, so called “tapered flocculation”. The bigger-formed flocs can penetrate through the void of media. Subsequently, the collision between flocs in the void of media promoted the larger flocs (Culp, 1977; Luttinger, 1981 and Kludpiban, 2000). Moreover, the overdosing of coagulant (10 mg/L) could result in media clogging, rapid headloss development and turbidity breakthrough. Finally, the poor effluent water quality was produced. On the other hand, if the coagulant dosage was too low, the chemical coagulation-flocculation would not be completed resulting the high turbidity of effluent water.

Table 5 Performance of single floating media flocculator at different dosages of PACl and different hydraulic rates (layer depth of 60 cm. and media size of 3 mm)

Run no.	Hydraulic rates (m^3/m^2-h)	PACl doses (mg/L)	Average %Tb removal	Headloss development (mm)/ h	Expanded depth (cm)	Average G (s^{-1})	Average max. floc (μm)
1	2.5	10	86.1	21 mm / 6 hr	0.1	29.8	292
2	2.5	5	94.9	12 mm / 6 hr	0.1	20.4	393
3	2.5	2.5	95.2	10 mm / 8 hr	0.1	20.4	393
4	5	40	70.9	65 mm / 6 hr	0.2	57.8	254
5	5	10	85.9	43 mm / 6 hr	0.1	42.4	274
6	5	5	90.5	42 mm / 6 hr	0.1	41.5	289
7	5	2.5	91.4	31 mm / 9 hr	0.1	43.5	340
8	5	1.25	82.5	52 mm / 24 hr	0.2	45.7	336
9	10	40	55.3	44 mm / 6 hr	0.5	84.9	137
10	10	10	73.6	52 mm / 6 hr	0.2	76.8	153
11	10	5	75.5	49 mm / 6 hr	0.2	76.1	190
12	10	2.5	79.9	49 mm / 7 hr	0.6	77.4	255
13	10	1.25	69.4	37 mm / 6 hr	0.2	66.7	161

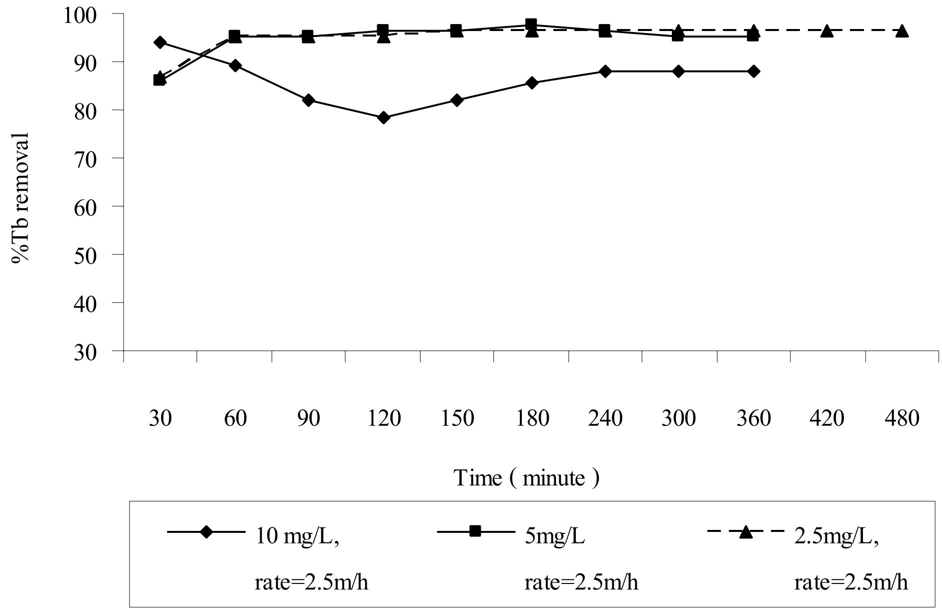


Figure13 Turbidity removal of the single floating-media (3-mm bead diameter, 60-cm layer depth) flocculator at different dosages of PACl under the hydraulic rate of 2.5 m^3/m^2-h.

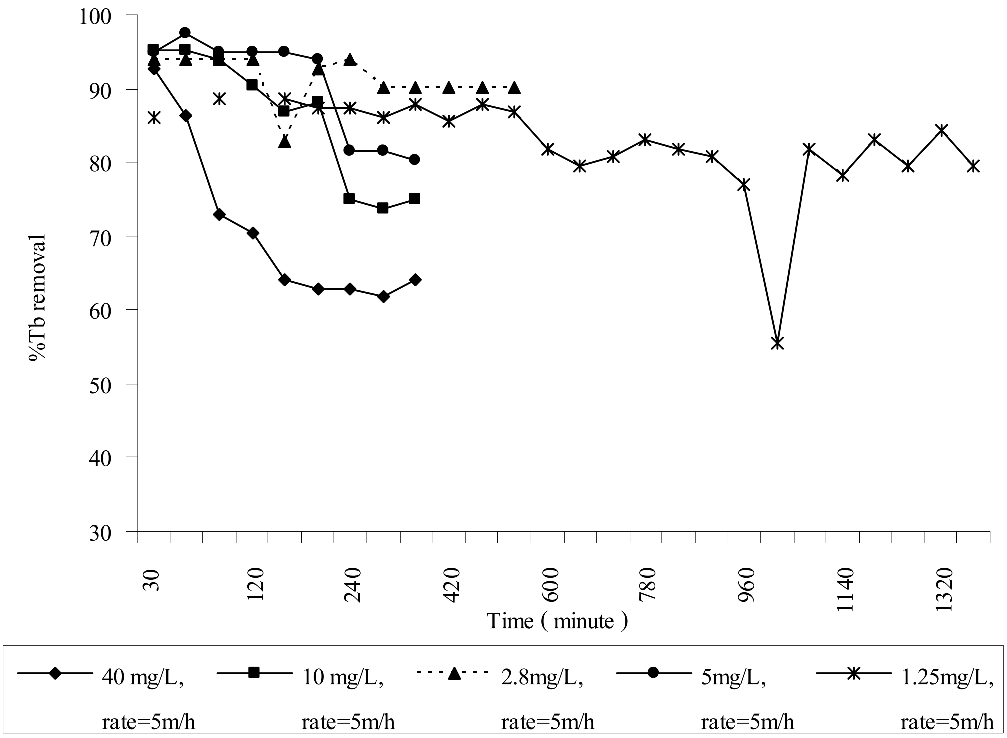


Figure 14 Turbidity removal of single floating-media (3-mm bead diameter, 60-cm layer depth) flocculator at different dosages of PACl under the hydraulic rate of 5 m^3/m^2-h.

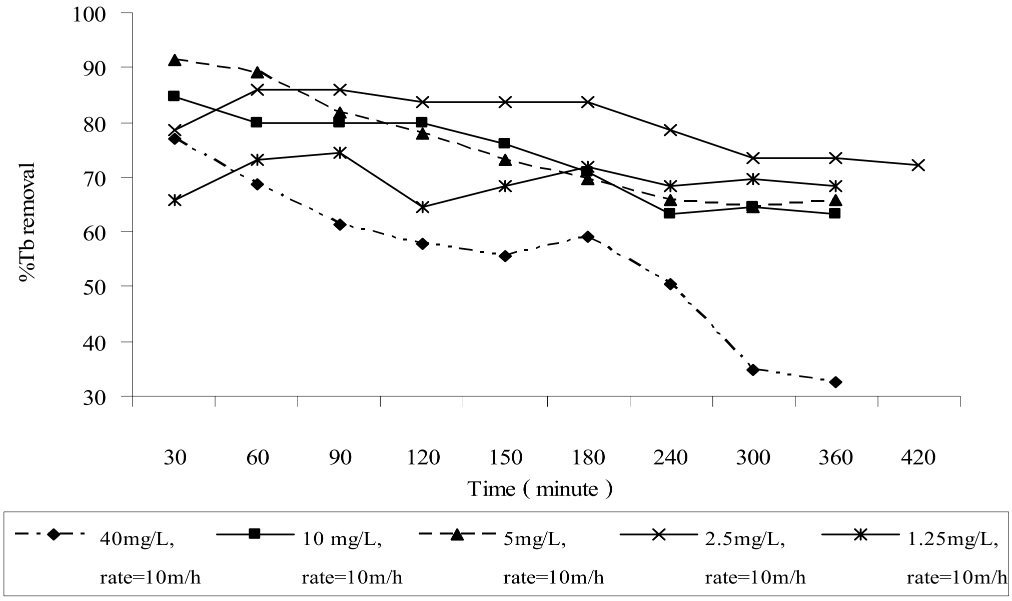


Figure 15 Turbidity removal of single floating-media (3-mm bead diameter, 60-cm layer depth) flocculator at different dosages of PACl under the hydraulic rate of 10 m^3/m^2-h.

2.1.2 Effect of PACl doses on headloss development

Figures 16-18 represented the performance of system in terms of head loss development (in cm) at different PACl doses of hydraulic rates of 2.5 m^3/m^2-h, 5 m^3/m^2-h and 10 m^3/m^2-h, respectively. As can seen in Figure 16, the accumulated headloss development was observed to be very low. The headloss developments were found to be 10 mm within 8 hours, 12 mm within 6 hours and 21 mm within 6 hours for the experiments using PACl doses of 2.5 mg/L, 5 mg/L and 10 mg/L, respectively. The similar results were found in Figure 17. From Figure 17, the headloss development was found to be only 52 mm within 24 hours, 31mm within 9 hours, 42 mm within 6 hours, 43 mm within 6 hours and 65 mm within 9 hours at PACl doses of 1.25 mg/L, 2.5 mg/L, 5 mg/L, 10 mg/L and 40 mg/L, respectively.

From Figure 18, the headloss developments were found to be 37 mm within 6 hours, 49 mm within 7 hours, 49 mm within 6 hours, 52 mm within 6 hours and 44 mm within 9 hours at PACl doses of 1.25 mg/L, 2.5 mg/L, 5 mg/L, 10 mg/L and 40 mg/L, respectively. Because of the flocculation mechanisms in the floating-media column, the higher dose led to greater clogging, larger expansion of floating media depth and quicker detachment of flocs from media. (Ngo and Vigneswaran, 1995a, 1995b). As can seen in Figure 18, the headloss development of 40-mg/L PACl dosage was reduction from 55 mm to 41 mm after the media layer expanded about 4 mm. Then, the flocs had started to fall down from media while media was expanding. This occurrence caused the deterioration of effluent quality.

From Figures 16-18, it was observed that the higher dosage of coagulant caused the higher headloss development. The floc volume was proportional to the coagulant dosage used. The higher dosage resulted in the large volume of flocs and the rapid clogging in porous media resulting the shorter operating time. (Adin and Rebhun,1974).

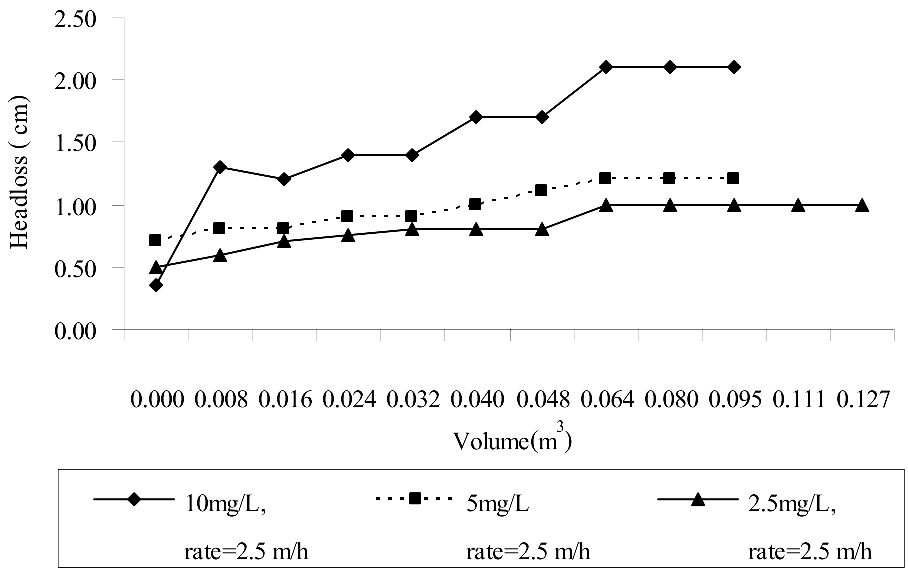


Figure 16 Throughput of single floating-media (3-mm bead diameter, 60-cm layer depth) flocculator at different doses of PACl under hydraulic rate of 2.5 m^3/m^2-h

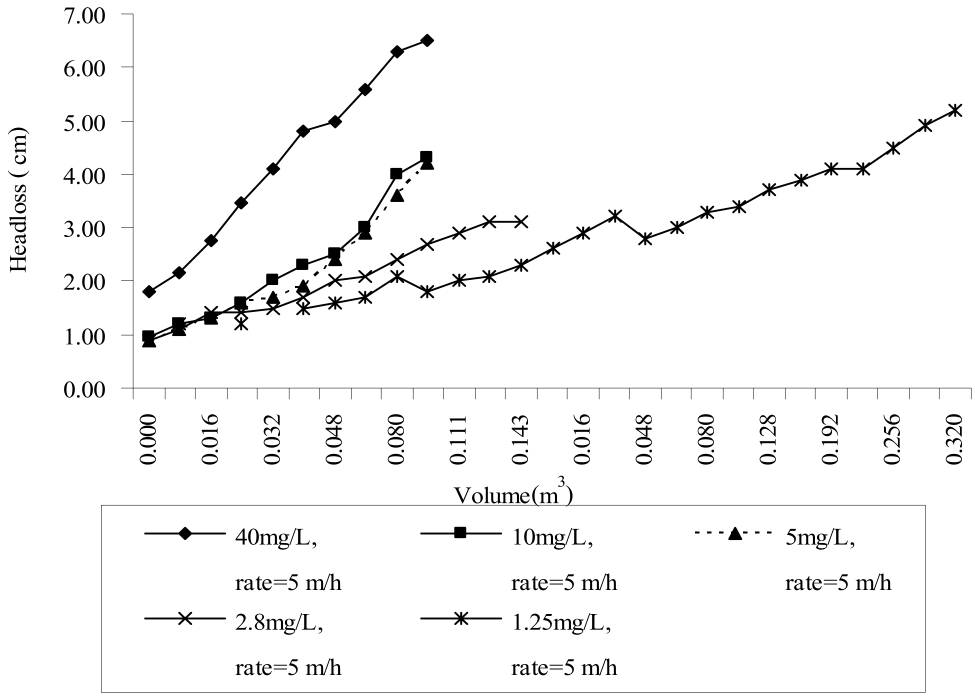


Figure 17 Throughput of single floating-media (3-mm bead diameter, 60-cm layer depth) flocculator at different dosages of PACl under hydraulic rate of 5 m^3/m^2-h.

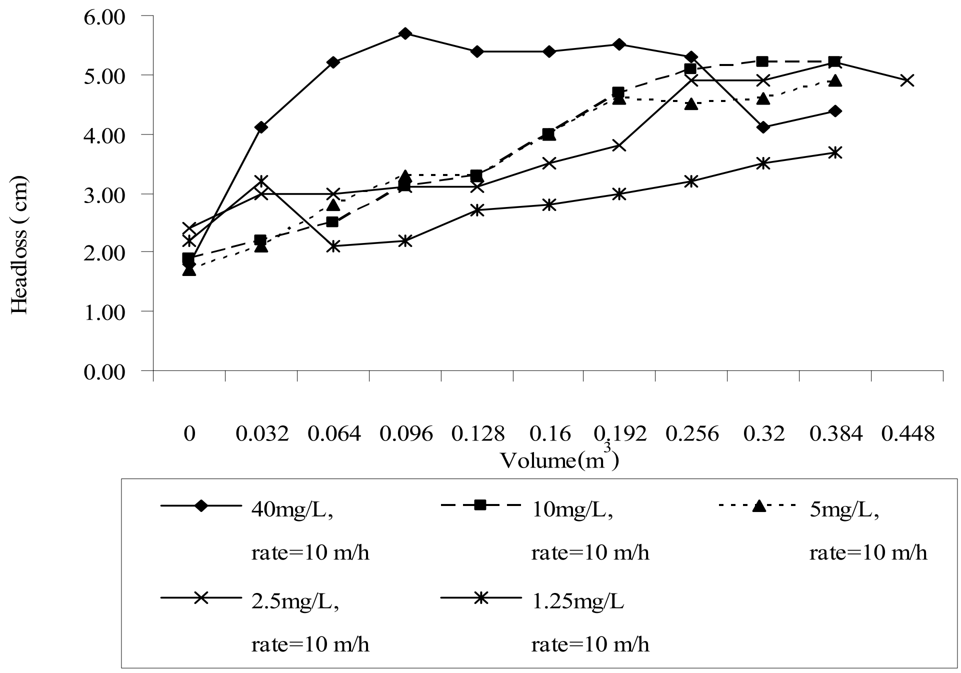


Figure 18 Throughput of single floating-media (3-mm bead diameter, 60-cm layer depth) flocculator at different dosages of PACl under hydraulic rate of 10 m^3/m^2-h

2.2 Effect of hydraulic rates.

2.2.1 Effect of hydraulic rates on turbidity removal percent

Figures 19-23 illustrate the performance of system in terms of turbidity removal with different hydraulic rates and different PACl doses of 1.25 mg/L, 2.5 mg/L, 5 mg/L, 10 mg/L and 40 mg/L. From Figure19, the average turbidity removals were 82.5% and 69.4% at the hydraulic rates of 5 m^3/m^2-h and 10 m^3/m^2-h, respectively. From Figure 20, the average turbidity removals were 95.2%, 91.4% and 79.9% at the hydraulic rates of 2.5 m^3/m^2-h, 5 m^3/m^2-h and 10 m^3/m^2-h, respectively. From Figure 21, the average turbidity removals were 94.9%, 90.5% and 75.5% at the hydraulic rates of 2.5 m^3/m^2-h, 5 m^3/m^2-h and 10 m^3/m^2-h, respectively. From Figure 22, the average turbidity removals were 86.1%, 85.9% and 73.6% at the hydraulic rates of 2.5 m^3/m^2-h, 5 m^3/m^2-h and 10 m^3/m^2-h, respectively. From Figure23, the average turbidity removals were 70.9% and 55.3% at the hydraulic rates of 5 m^3/m^2-h and 10 m^3/m^2-h, respectively.

With reference to Figures 19-23, it can be seen that an increase in hydraulic rate reduced effluent water quality in term of decreasing turbidity removal efficiency (in percentage). It was observed that application of hydraulic rate at 2.5 m^3/m^2-h could produce the highest turbidity removal for any coagulant dose. From Table 5, the highest average turbidity removals at the hydraulic rate of 2.5 m^3/m^2-h were 86.1%, 94.9% and 95.2% with the PACl doses of 10 mg/L, 5 mg/L and 2.5 mg/L, respectively.

Increasing the hydraulic rate increased the rate of floc deposit on the floating beads. This had an additional effect of increasing the interpore shear forces. If the shear forces exceeded the attachment forces, floc would be pushed from the surface of media prior to capture. The net result was the reduction in effluent quality.

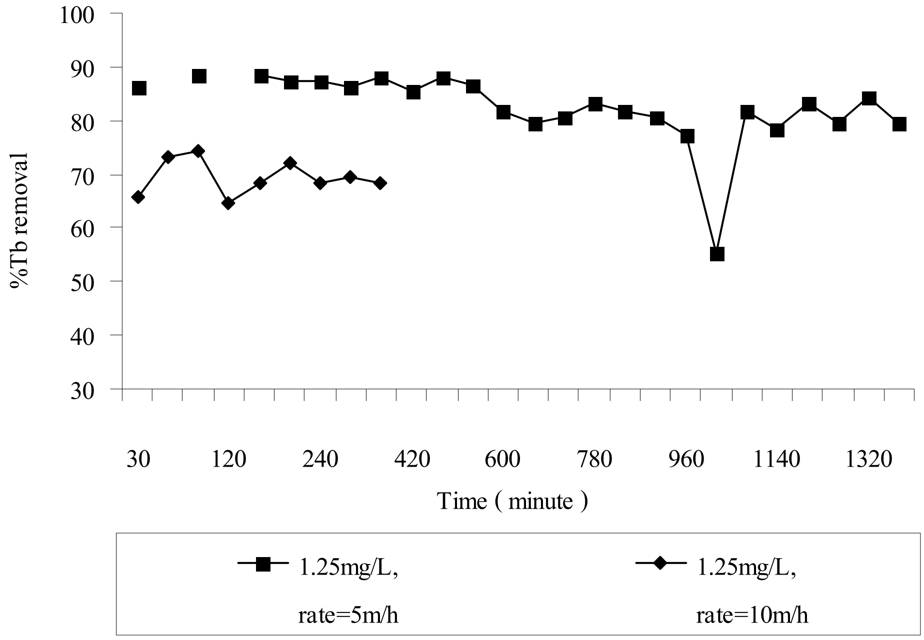


Figure 19 Turbidity removal of single floating-media (3-mm bead diameter, 60-cm depth) flocculator at different hydraulic rate on PACl dose of 1.25 mg/L

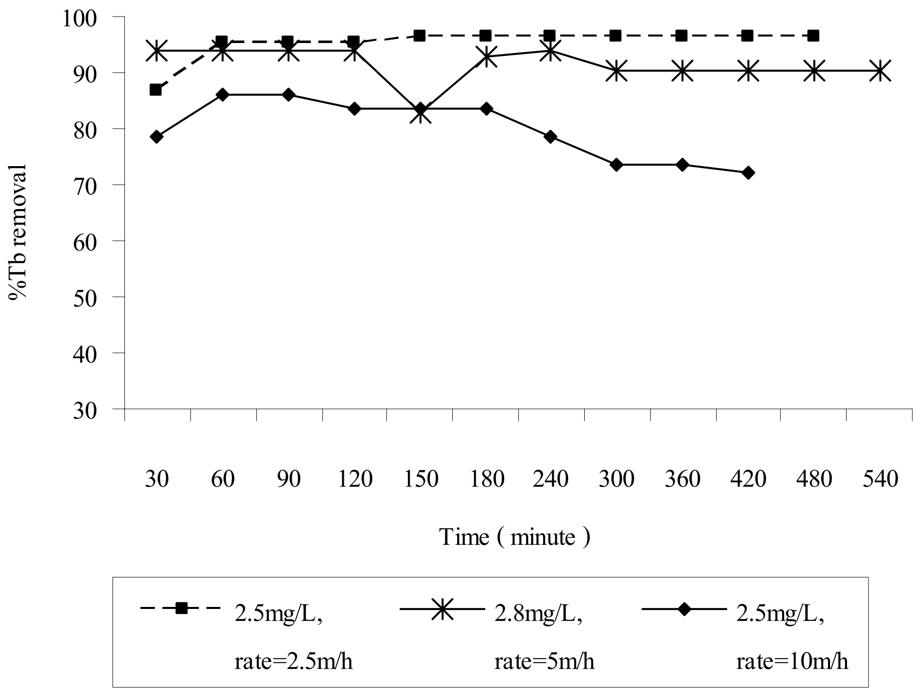


Figure 20 Turbidity removal of single floating-media (3-mm bead diameter, 60-cm depth) flocculator at different hydraulic rates on PACl dose of 2.5 mg/L

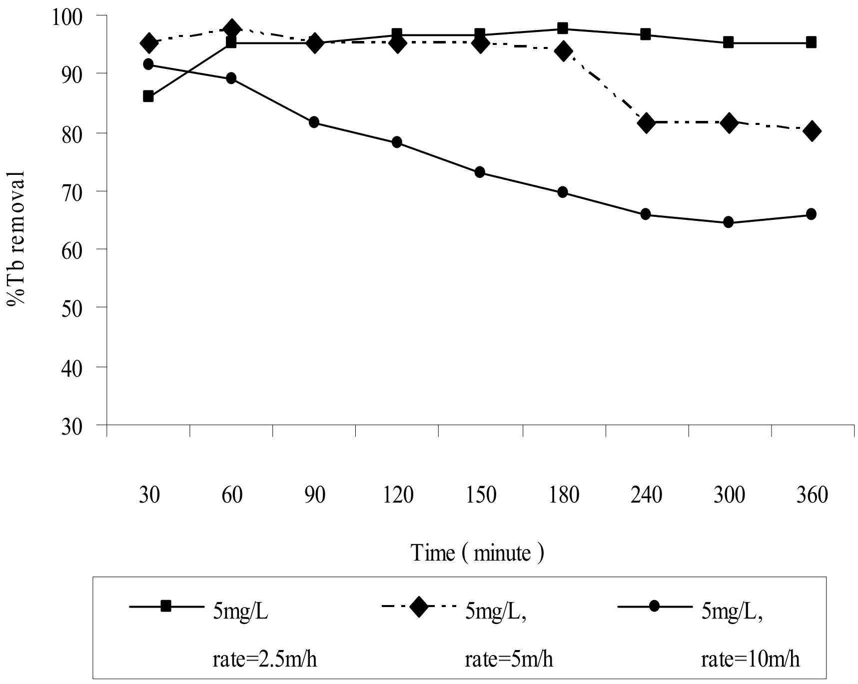


Figure 21 Turbidity removal of single floating-media (3-mm bead diameter, 60-cm depth) flocculator at different hydraulic rates on PACl dose of 5 mg/L

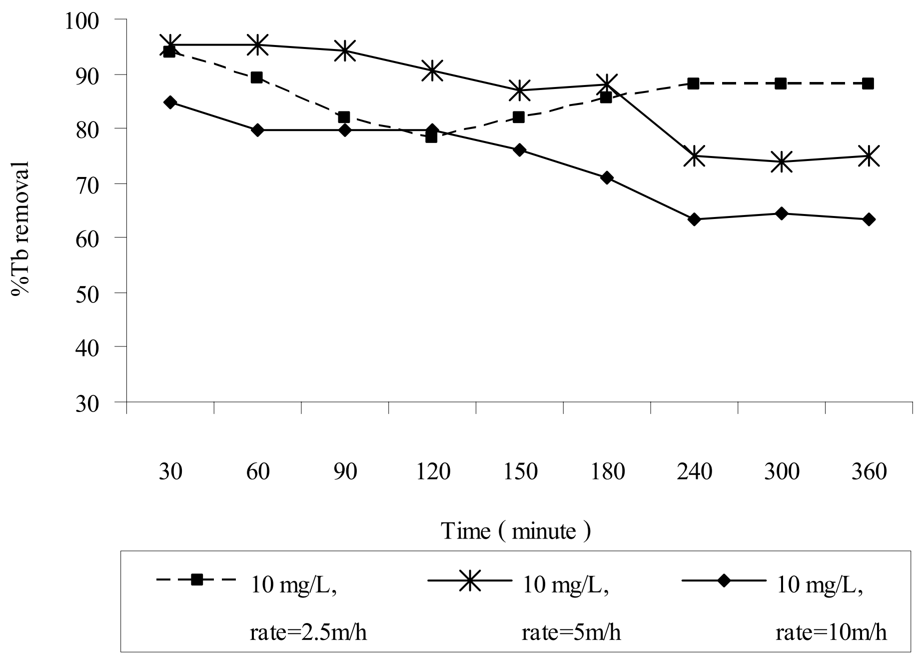


Figure 22 Turbidity removal of single floating-media (3-mm bead diameter, 60-cm depth) flocculator at different hydraulic rates on PACl dose of 10 mg/L

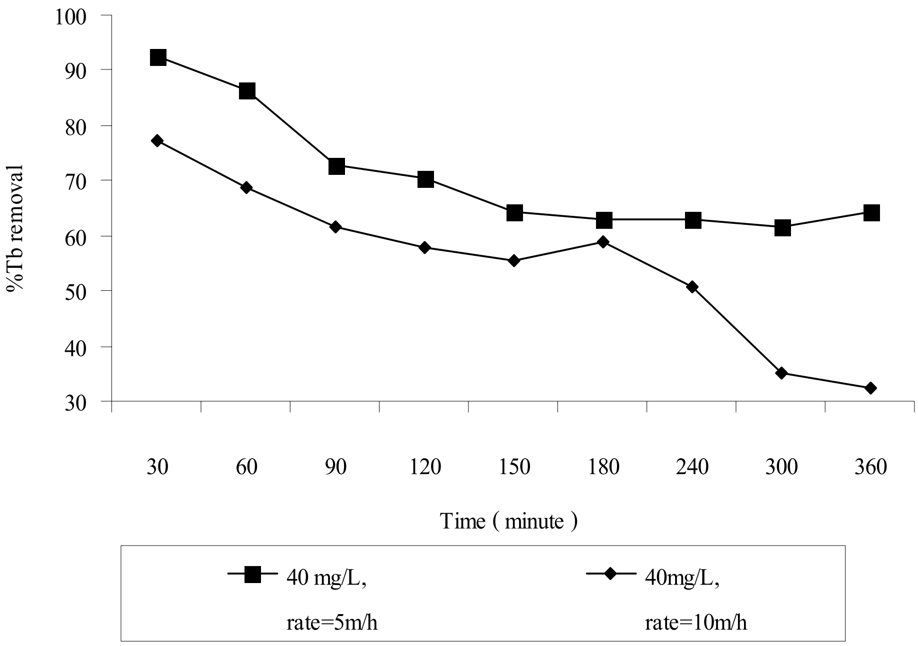


Figure 23 Turbidity removal of single floating-media (3-mm bead diameter, 60-cm depth) flocculator at different hydraulic rates on PACl dose of 40 mg/L

2.2.2 Effect of hydraulic rates on headloss development

The comparison of the accumulated headloss development with the same dosages of PACl (40 mg/L, 10 mg/L, 5 mg/L, 2.5 mg/L and 1.25 mg/L), but different hydraulic rates were shown in Figures 28-32. As can seen in Figure 28, the headloss developments were observed to be 65 mm within 6 hours and 44 mm within 6 hours at the hydraulic rates of 5 m^3/m^2-h and 10 m^3/m^2-h, respectively . As mention before, the headloss development of 40-mg/L PACl dosage under the hydraulic rate of 10 m^3/m^2-h reduced from 55 mm to 41 mm because of bed expansion.

From Figure 24, the headloss developments were found to be 21mm within 6 hours, 43 mm within 10 hours and 52 mm within 6 hours at the hydraulic rates of 2.5 m^3/m^2-h, 5 m^3/m^2-h and 10 m^3/m^2-h, respectively. The finding showed that higher hydraulic rate provided the higher headloss development for all of PACl doses because the headloss was the functions of floc volume retained in bed, cross-section area of bed, size of media and flow rate (O'Melia and Ali, 1978; Equation no.8,9). The higher rate increased the rate of retained-floc volume and headloss accumulation until reached the point that bed expanded. The floc pulled down from bed resulting in lower headloss. The same results were also found in Figures 25-28.

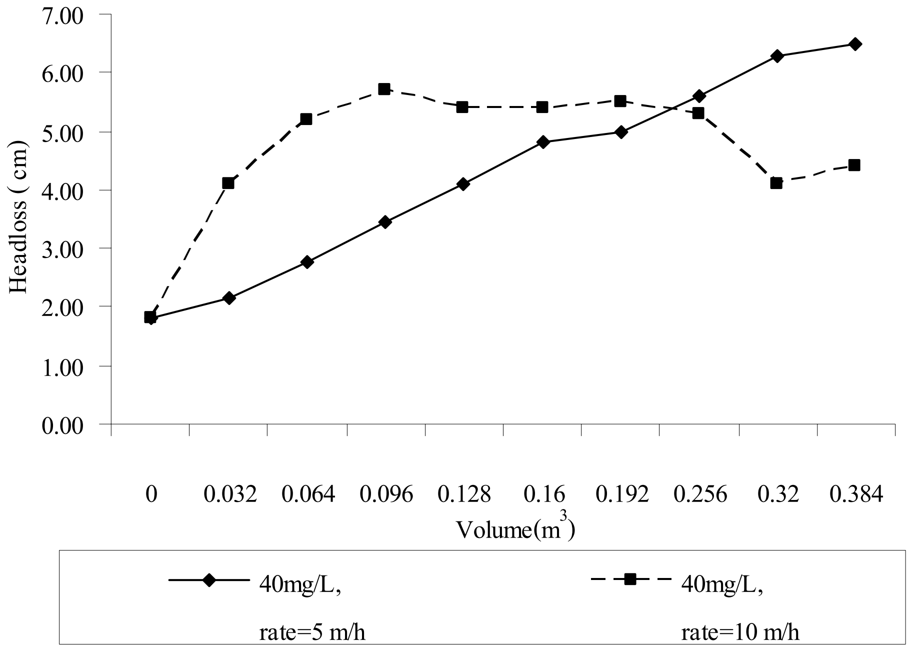


Figure 24 Throughput of single floating-media (3-mm bead diameter, 60-cm layer depth) flocculator at different hydraulic rates on dose of PACl of 40 mg/L

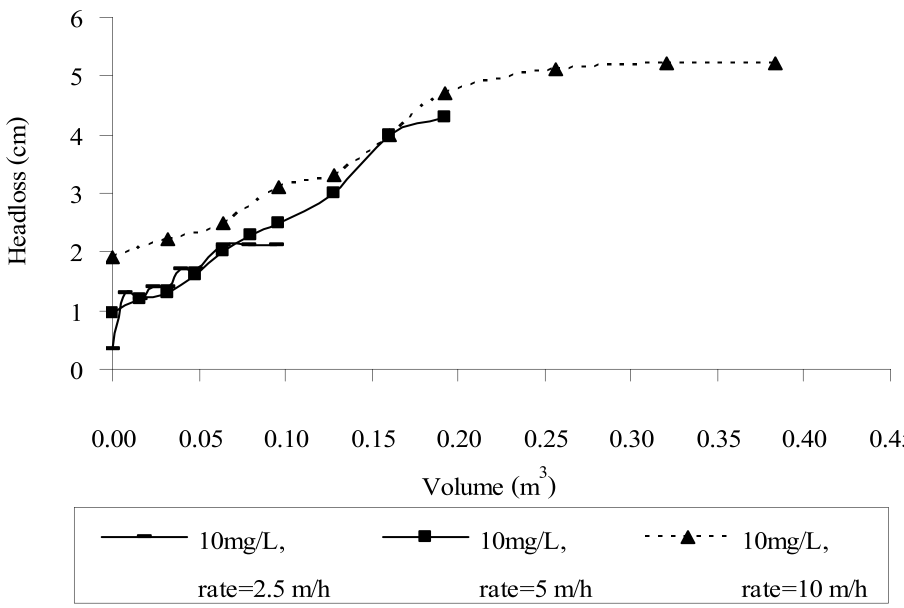


Figure 25 Throughput of single floating-media (3-mm bead diameter, 60-cm layer depth) flocculator at different hydraulic rates on dose of PACl of 10 mg/L

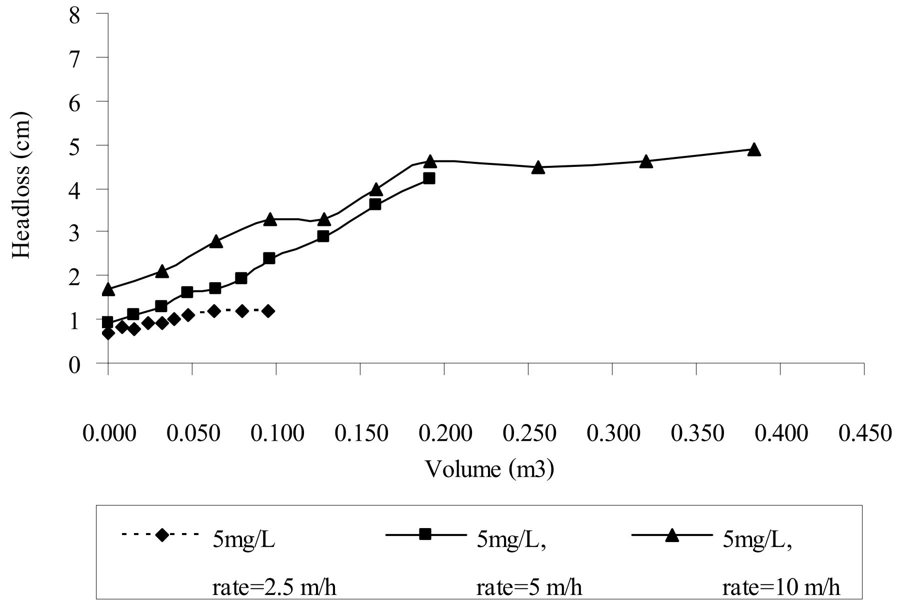


Figure 26 Throughput of single floating-media (3-mm bead diameter, 60-cm layer depth) flocculator at different hydraulic rates on dose of PACl of 5 mg/L

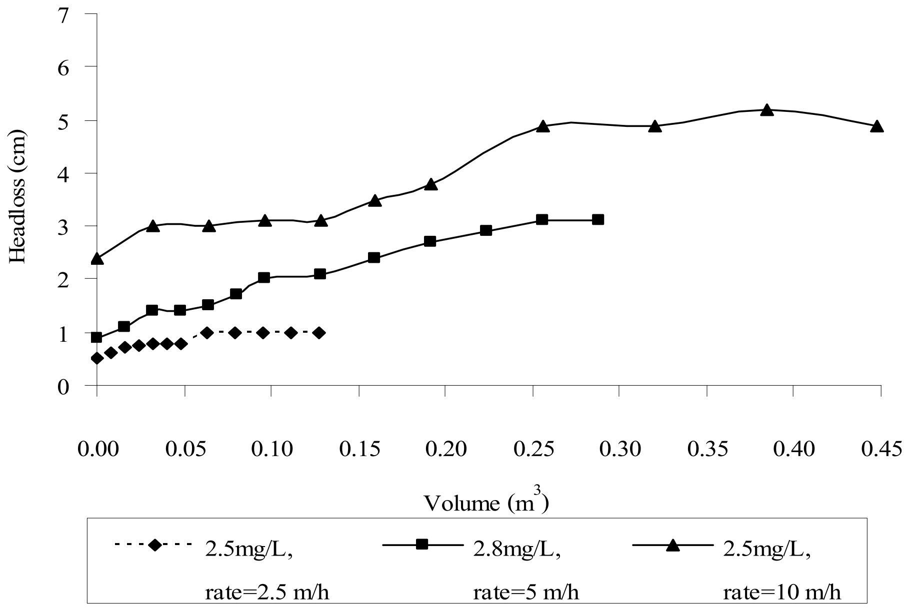


Figure 27 Throughput of single floating-media (3-mm bead diameter, 60-cm layer depth) flocculator at different hydraulic rates on dose of PACl of 2.5 mg/L

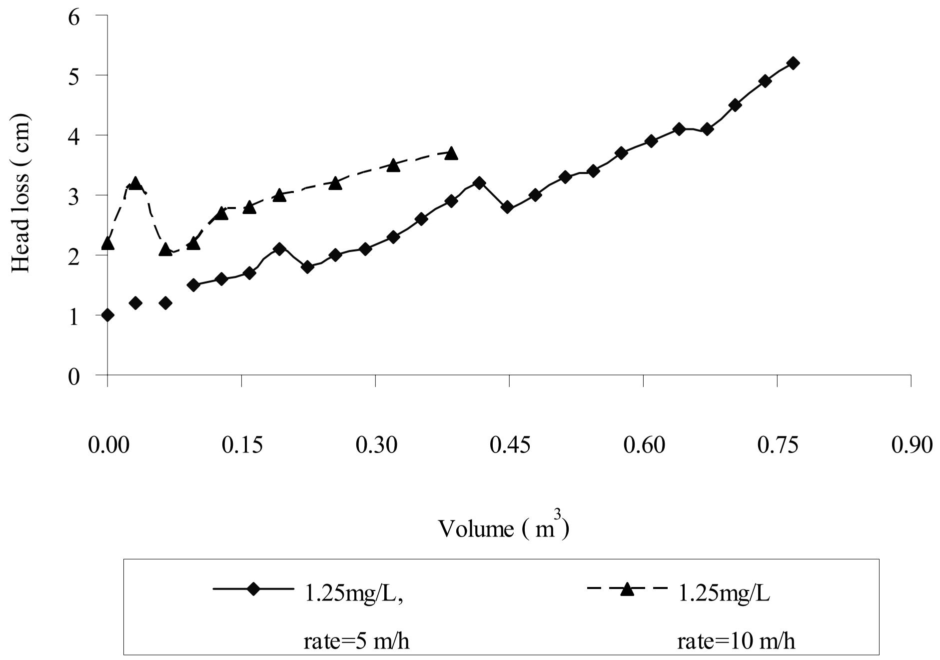


Figure 28 Throughput of single floating-media (3-mm bead diameter, 60-cm layer depth) at flocculator different hydraulic rates on dose of PACl of 1.25 mg/L

2.2.3 Effect of hydraulic rates on average maximum floc size

As mentioned above, the velocity gradient was dictated by headloss. The headloss was a function of flow rate. Shear forces due to too high velocity gradient could break up larger floc and limit the maximum floc size. Consequently, the higher hydraulic rate produced the higher velocity gradient resulting in decreasing of maximum floc size. From Table 5, the maximum average floc size decreased with increasing in hydraulic rate (at same PACl dose).

3. **Influence of media size on performance of floating media flocculator.**

This study was done by applying floating media of polypropylene beads with different diameters of 3 mm, 6 mm and 10 mm approximately and a layer depth of 30 cm. The synthetic raw water using kaolin clay with an approximate turbidity of 80 NTU was prepared. The performance of floating media flocculator was examined using PACl dosage of 2.5-mg/L. The system was operated under the hydraulic rate of 2.5 m^3/m^2-h.

Table 6 Performance of single floating media flocculator at different media size (layer depth of 30 cm. and media size of 3 mm, 6 mm and 10 mm)

Run no.	Hydraulic rate (m^3/m^2-h)	Media size (mm)	Accumulate headloss (mm)	Average velocity gradient (s^{-1})	Maximum floc size (μm)
16	2.5	3	9	19.0	922
14	2.5	6	3	12.8	1114
18	2.5	10	2	10.5	1913

The headloss developments with different media sizes at the hydraulic rate 2.5 m^3/m^2-h were illustrated in Figure29. The smaller media resulted in the higher headloss development. The headloss was caused by the accumulation of flocs within media bed. By base on equations (8) and (9) (O'Melia and Ali, 1978), the headloss was the functions of floc size and pore size. Therefore, the smaller media pore size would greater effect on the headloss development. From Table 6, the accumulated headlosses were 9 mm, 3 mm and 2 mm with media sizes of 3 mm, 6 mm and 10 mm, respectively.The average maximum floc sizes were 922 μm, 1114 μm and 1913 μm with the media sizes of 3 mm, 6 mm and 10 mm, respectively. As mentioned before, the velocity gradient was proportional to headloss development. The smaller media size yielded the higher headloss development. Consequently, the smaller size of media also yielded the higher velocity gradient resulting in decreasing of maximum floc size

The overall results could be concluded that the increase of media size resulted in the decrease of headloss development and the increase of average maximum floc size.

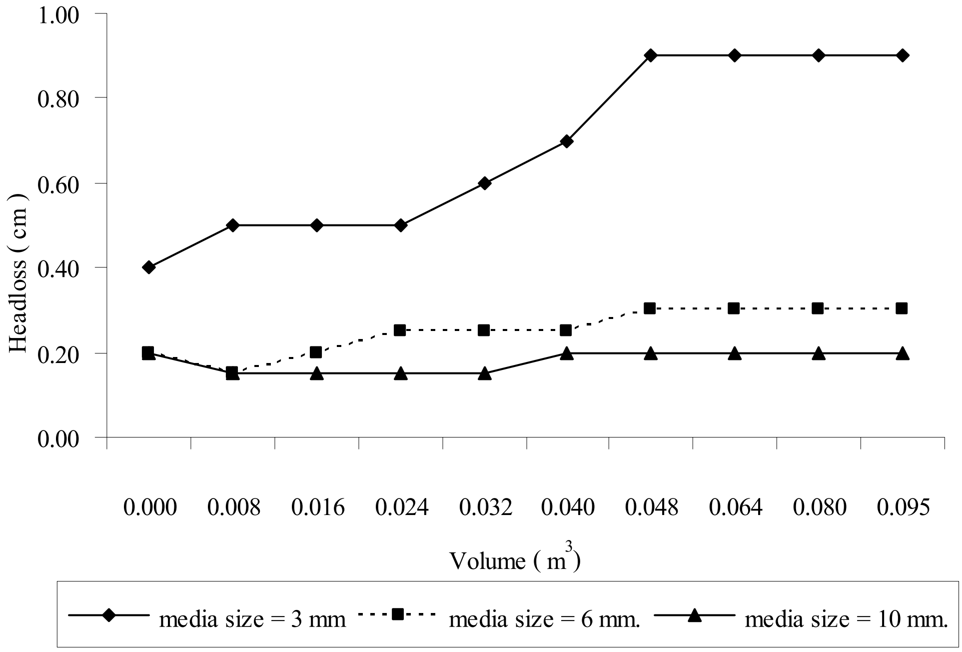


Figure 29 Throughput at different media size (3-mm, 6-mm and 10-mm bead diameter, 30-cm layer depth) flocculator under hydraulic rate of 2.5 m^3/m^2-h and PACl dose of 2.5 mg/L

4. Performance of single and multilayer floating-media flocculator

This study was done by applying floating media of polypropylene beads with a diameter of about 3 mm, 6 mm and 10 mm. The floating-media flocculator was operated as single, dual and multilayer configuration at the layer depth of 30 cm and 60 cm The performance of floating-media flocculator was examined using the optimum conditions obtained from experiments no.1-13 (influent turbidity of 80 NTU, 2.5 mg/L of PACl dose and hydraulic rate of 2.5 m^3/m^2-h).

The overall performance of single and multilayer floating-media flocculator was considered. Figures 30-31 demonstrate that the smallest single media produced the highest headloss and smallest maximum floc size (3-mm bead diameter). Whilst the biggest single media produced the lowest headloss and the biggest maximum floc size (10-mm bead diameter). From Table 7, the multilayer floating media yielded the same trend of results as described below:

- The multilayer floating media decreased headloss when compared with the smaller single media because of this system allowing fine floc to penetrate deeper in to the coarse media and more area of media utilized;
- The multilayer floating media produced bigger floc formed when compared with the smaller single media because of the grading size of media resulting in tapered flocculation.

As seen in Table7, the longer media depth produced longer detention time in bed resulting in higher *GT* or Camp number. The higher *GT* yielded the smaller maximum floc size when compared at the same size of media. However, the changes in parameter *GT* were not corresponding to the changes in floc size when the different media sizes were applied. Therefore, the next study should be study the other parameter that effected on floc size excepting *GT*.

It could be concluded that the bigger size and shorter depth of media succeeded in producing bigger floc formation and lower headloss development.

Table 7 Performance of single and multilayer floating media system

Run no.	Media size(mm);			Media depth (cm);	Velocity gradient (s^{-1}); G	Detention time in media (s); T	GT	Max . floc (μm); d_S	Accumulate headloss (cm)
14	6	-	-	30	13.3	156	2073	1114	0.30
15	6	-	-	60	14.0	311	4365	980	0.40
16	3	-	-	30	21.7	147	3188	922	0.90
17	3	-	-	60	22.4	294	6573	755	1.10
18	10			30	11.0	173	1908	1913	0.20
19	10	-	-	60	11.5	346	3960	1739	0.40
20	6	10	-	30	13.3	164	2177	1757	0.25
21	6	10	-	60	13.6	328	4470	1274	0.50
22	3	6	-	30	16.6	151	2518	1186	0.40
23	3	6	-	60	17.3	302	5234	891	0.80
24	3	10	-	60	16.9	160	2702	1007	0.60
25	3	10	-	60	17.7	320	5662	857	0.90
26	3	6	10	30	15.8	158	2496	1750	0.40
27	3	6	10	60	16.0	317	5080	1662	0.70

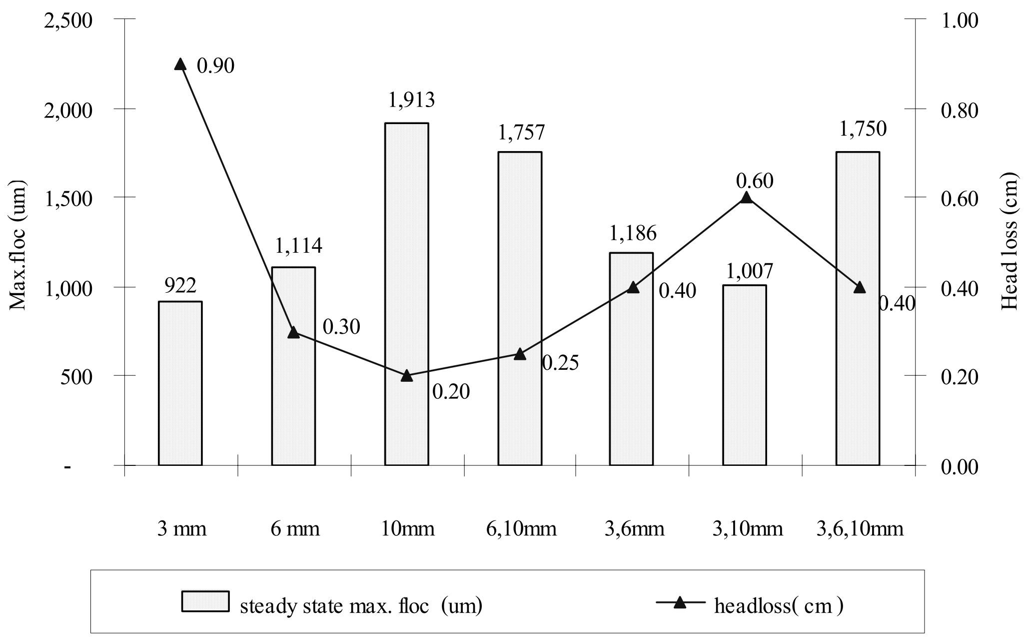


Figure 30 Performance of single and multilayer floating media at layer depth of 30 cm under hydraulic rate of 2.5 m^3/m^2-h and PACl dose of 2.5 mg/L

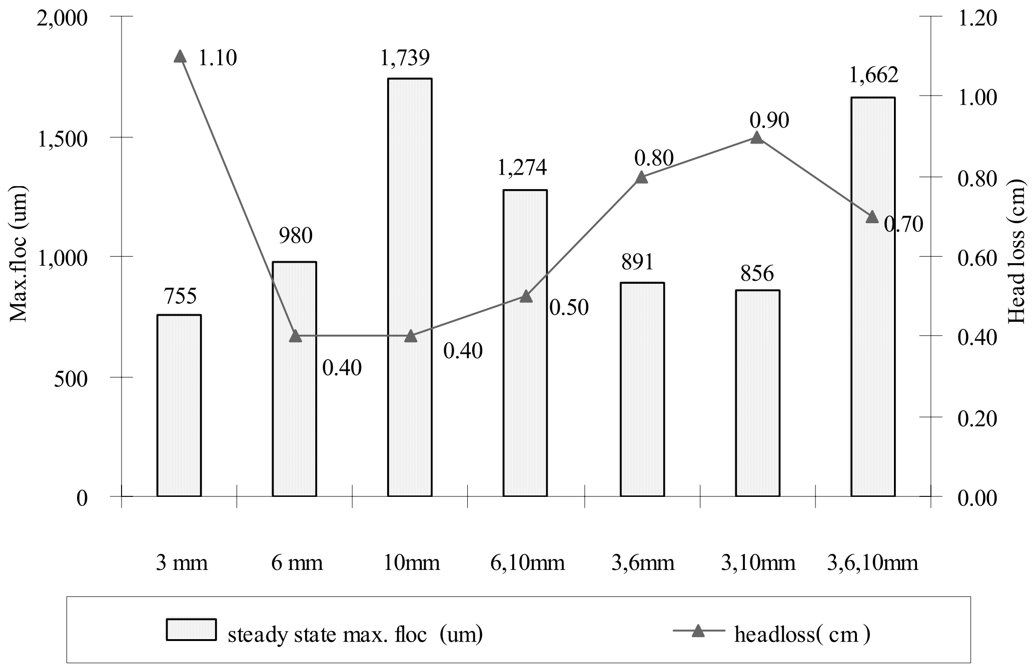


Figure 31 Performance of single and multilayer floating media at layer depth of 60 cm under hydraulic rate of 2.5 m^3/m^2-h and PACl dose of 2.5 mg/ L

Mathematical Modeling

1. Coefficients related to floc strength at different PACl doses

This study was done by applying floating media of polypropylene beads with the diameters of 3 mm bead depth at layer of 60 cm (run no.1-13). The synthetic raw water using kaolin clay with an approximate turbidity of 80 NTU. The polyaluminium chloride doses of 40 mg/L, 10 mg/L, 5 mg/L, 2.5 mg/L and 1.25 mg/L were applied to the multilayer floating-media flocculation under the hydraulic rates of 10 m^3/m^2-h, 5 m^3/m^2-h and 2.5 m^3/m^2-h.

The coefficients related to floc strength such as C_S and n for the experiments using different PACl doses were determined by linearization of the equation (2). The values of n and ln C_S were found from a ln–ln plot of the maximum floc size (d_S) against velocity gradient (G). Figure 32 shows the plot of the maximum floc size (d_S) and the velocity gradient (G) at different PACl doses. The values of C_S and n coefficients at each PACl dose were summarized in Table 8

Table 8 The values of C_S and n at different PACl doses

PACl dose (mg/L)	Ln C_S	C_S	n
40	10.4	32860	0.85
10	9.8	18034	0.68
5	9.6	14765	0.67
2.5	9.4	12088	0.59
1.25	7.3	1480	0.25

As mentioned before, the value of C_S (y-axis intercept) provided an indication of maximum size of d_S when flocs were formed at a given velocity gradient. The value of n indicated how flocs responded to subsequent increasing in shear rate. The higher value of n yielded more opportunity of flocs break-up into smaller size with increasing velocity gradient. From Table 8, the higher PACl dose resulted in the bigger size of floc and the higher sensitivity to break-up under different shear conditions (Figure 4)

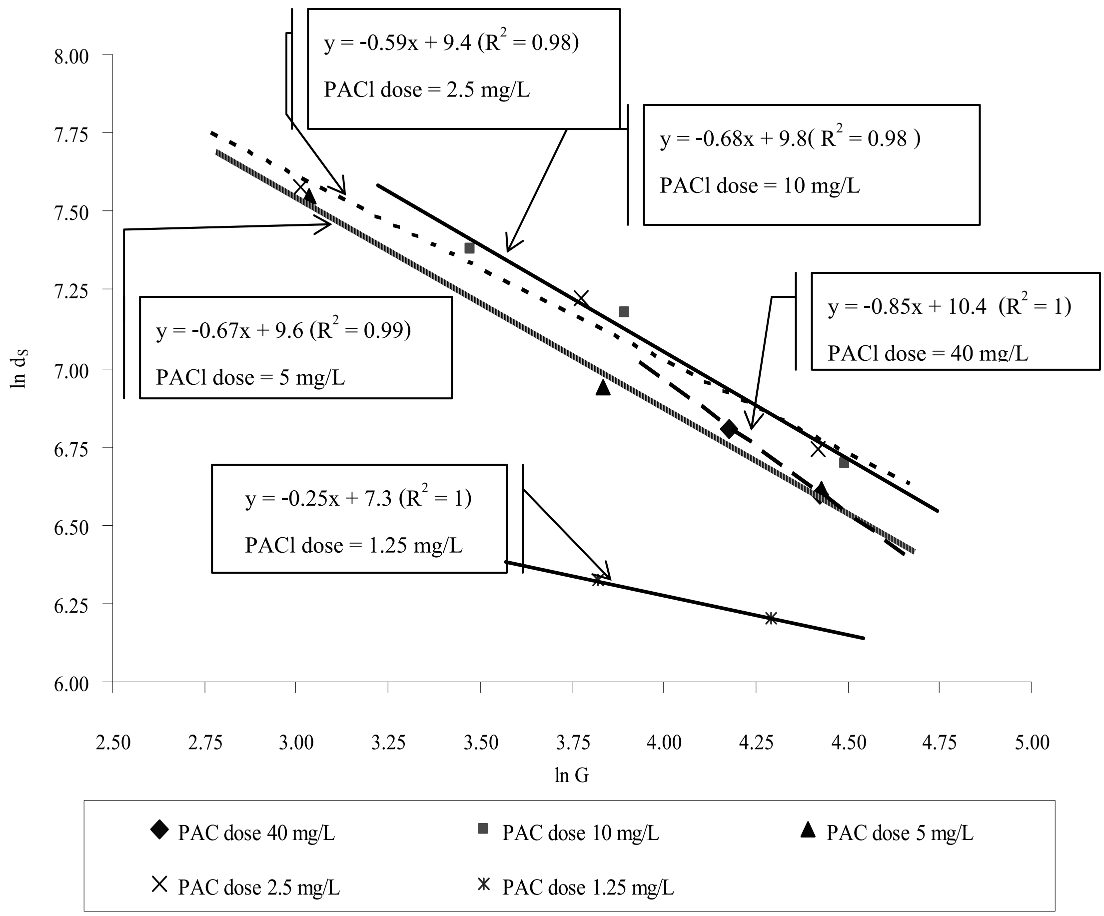


Figure 32 Relationship between velocity gradient (G) and the maximum floc (d_S) at different PACl doses

2. Coefficients related to floc strength of single media

This study was done by applying floating media of polypropylene beads with the diameters of 3, 6 and 10 mm. The single-layer floating-media flocculator was operated with layer depths of 30 cm and 60 cm (run no.14-19). The synthetic raw water with an approximate turbidity of 80 NTU and the optimum condition from experiments no.1-13 (influent turbidity of 80 NTU, 2.5 mg/L of PACl dose and hydraulic rate of 2.5 m^3/m^2-h) was used to operate system.

Linearization of the equation (2) allowed the values of n and ln C_S to be found from a ln–ln plot of the maximum floc size (d_S) against velocity gradient (G). Figure33 shows the plot of the maximum floc size (d_S) and velocity gradient (G) in single floating-media flocculation system. The data fitting showed that the empirical equation obeyed the equation of Parker (Parker *et al.*, 1972). The coefficients related to floc strength such as C_S and n were found to be 19,798 (ln C_S= 9.89) and 1.04, respectively. The empirical equation for single floating media flocculator in this experiment could be written as: d_S= 19,798$G^{-1.04}$

Table 9 Maximum floc size at different velocity gradient of single media flocculator

Media size (mm)	Media depth (cm)	Maximum floc size; d_S (µm)	Velocity gradient; G (s^{-1})	ln d_S	ln G
3	30	922	21.7	6.8	3.1
3	60	755	22.4	6.6	3.2
6	30	1,114	13.3	7.0	2.6
6	60	980	14.0	6.9	2.6
10	30	1,913	11.0	7.6	2.4
10	60	1,739	11.5	7.5	2.5

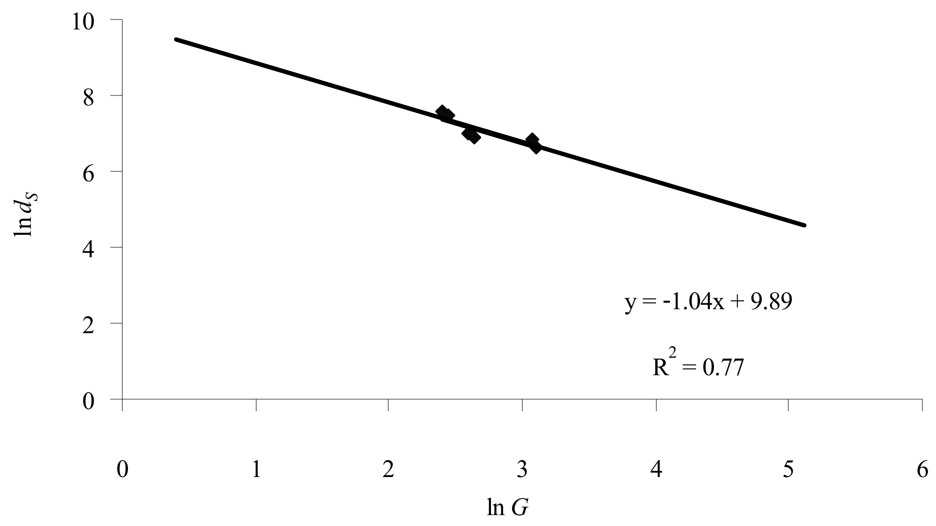


Figure 33 Maximum floc size at different velocity gradient of single media flocculator

3. Relationship between d_S from single media and d_S from multilayer media

This study was done by applying floating media of polypropylene beads with the diameters of 3, 6 and 10 mm. The multilayer floating-media flocculator was operated with the layer depths of 30 cm and 60 cm (run no.20-27). The optimum condition from experiments no.1-13 (influent turbidity of 80 NTU, 2.5 mg/L of PACl dose and hydraulic rate of 2.5 m^3/m^2-h) was used.

The relationship between the maximum floc size (d_S) in multilayer floating media and velocity gradient (G) were estimated by using the coefficients related to floc strength (C_S and n) of single floating media.

The maximum floc size (d_S) of dual and multilayer floating plastic media were predicted from equation as shown below.

$$d_{S,N} = C_S * \sum_{i=1}^{N} G^{-1.04} \tag{16}$$

where C_S and n obtained from the single floating-plastic-media experiment. Since the C_S and n coefficients obtained from the single media column were 19,798 and 1.04, respectively. Then, the values of C_S and n were substituted into equation no.16. All results are shown in Table 10

<u>Table 10</u> Maximum floc size of dual and multilayer floating plastic media flocculator

Media size (mm)			Velocity gradient (s^{-1})			d_S-observe (µm)	d_S-predict (µm)	R	d_S-predict *R
			top	medium	bottom				
3	6	-	12.8	12.2	-	1,186	2884	0.42	1186
3	6	-	15.6	13.3	-	891	2453	0.36	890
3	10	-	17.6	10.8	-	1,007	2639	0.38	1008
3	10	-	19.5	10.0	-	856	2676	0.32	856
6	10	-	12.5	7.4	-	1,757	3859	0.46	1756.
6	10	-	12.6	10.1	-	1,274	3168	0.40	1274
3	6	10	18.9	16.5	11.9	1,750	3468	0.51	1751
3	6	10	19.5	10.8	7.0	1,662	5133	0.32	1663

Remark: $d_{S,N}$– predict $= 19{,}798 * \sum_{i=1}^{N} G^{-1.04}$

: R = Correcting Factor

The results from Table 10 demonstrated that the values of d_S- predict (calculated) did not fit with d_S–observe (experimental). Therefore, the correcting factors were established. The values of correcting factor were in the range from 0.3 to 0.5.

CONCLUSIONS

1. The floating media flocculator required lower coagulant dosage than jar test to yield the bigger maximum floc size and the lower headloss development. The lower hydraulic rate produced the bigger maximum floc size and the lower headloss development. The multilayer floating media took an advantage over the single media in order to perform the better system performances such as lower headloss development and bigger floc formation.

2. The increase in velocity gradient (*G*) caused the decrease in maximum floc size (d_S). The empirical equation of single floating-plastic media could be written as $d_S = 19{,}798\ G^{-1.04}$ for the controlled experiment of 80-NTU influent turbidity, 2.5-mg/L PACl dose and 2.5-m^3/m^2-h hydraulic rate. Moreover, a simplified equation of d_S from the multilayer floating-media flocculator was proposed as $d_{S,\,N} = 19{,}798 * R * \sum_{i=1}^{N} G^{-1.04}$; where *R* was the correcting factor that had values between 0.3 to 0.5 under the controlled condition of 80-NTU influent turbidity, 2.5-mg/L PACl dose and 2.5-m^3/m^2-h hydraulic rate.

RECOMMENDATIONS

1. The system should be operated in long term for obtaining the steady-state maximum floc size.

2. The next study should target on the other parameters beside *GT* that effect on floc size.

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APPENDIXES

Appendix Table A1 Properties of Kaolin clay 200 mesh : Sample No. 47-016

SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	MgO (%)	CaO (%)	Na_2O (%)	K_2O (%)	TiO_2 (%)	P_2O_5 (%)	MnO (%)	Cr_2O_3 (%)	V_2O_5 (%)	LOI (%)	SUM (%)
68.7	20.3	0.88	0.21	0.11	2.06	3.02	0.03	0.02	0.08	<0.01	<0.01	4.41	99.8

Note : Whole Rock Analusis (WRA) by XRE, Exploration package

Source : Siam FineClay Co.,Ltd.

Appendix Table B1 Properties of Polypropylene

Typical	Data	Unit	Value	Test Method
Properties				
	MFI 2016 kg/230 °C	g/10 min	2.1	ASTM D 1238
	Tensile strength at yield	N/mm^2	23	ASTM D 638
	Charpy notched impact strength at 20 °C	mJ/mm^2	20	DIN 53453
	Shear modulas	N/mm^2	465	DIN 53457
	Ball indentation hardness	N/mm^2	55	DIN 53456
	Heat distortion temperature at 0.45 N/mm^2	°C	92	ASTM D 648
Application				
	For Injection molding with UV Stabilizer for Outdoor Application			
	Very high impact resistance for furniture, autopart, electical, appliance, toy, container, and agriculture product.			
Processing				
	Temperature 190 ~ 280 °C			

Source : Thai Petrochemical Industry Public Co.,Ltd.

Appendix Table C1 Properties of Polyaluminiumchloride (PAC) 30%

Appearance	Unit	Yellowish power
Aluminium oxide (Al_2O_3)	wt%	30% min
Basicity	wt%	65% min
pH Value (1% solution w/v)		3.5 ~ 5.0
Water insoluble matter	wt%	< 1.0 %
Iron (Fe)	wt%	< 1.0 %
Sulphate (SO_4)	wt%	< 0.1 %
Ammoniacal nitrogen (N)	wt%	0.03 max
Manganese (Mn)	mg/kg	45 max
Lead (Pb)	mg/kg	15 max
Cadmium (Cd)	mg/kg	3.0 max
Chromium (Cr)	mg/kg	15 max
Arsenic (As)	mg/kg	3.0 max
Mercury (Hg)	mg/kg	0.3 max

Source : LIANG CHEMI INTERNATIONAL CO.,LTD.

APPENDIX D

(EXPERIMENTAL DATA)

Appendix Table D1 Experimental data of run no.1

Time (min)	Tb (NTU)	pH	Temp (^{0}C)	Bed Expansion (cm) 1	2	3	Δh_1 (m)	Δh_2 (m)	Δh_3 (m)	Δh_4 (m)	Δh_5 (m)	% Tb removal	Max Floc (μm)
0	83	6.97	30	60.0	-	-	0.10	0.05	0.10	0.10	-	-	-
30	5	7.16	31	60.0	-	-	0.40	0.50	0.20	0.20	-	94.0	40
60	9	7.02	31	60.0	-	-	0.30	0.40	0.20	0.30	-	89.2	117
90	15	7.33	31.5	60.1	-	-	0.30	0.50	0.40	0.20	-	81.9	134
120	18	7.45	31.8	60.1	-	-	0.20	0.50	0.50	0.20	-	78.3	209
150	15	7.31	31.8	60.1	-	-	0.40	0.50	0.50	0.30	-	81.9	287
180	12	7.29	32	60.1	-	-	0.40	0.50	0.50	0.30	-	85.5	367
240	10	7.25	32	60.1	-	-	0.50	0.60	0.60	0.40	-	88.0	416
300	10	7.26	32	60.1	-	-	0.50	0.60	0.60	0.40	-	88.0	490
360	10	7.21	32	60.1	-	-	0.50	0.60	0.60	0.40	-	88.0	571

Time (min)	Porosity of media (f) Top layer	Medium layer	Bottom layer	$10^{-6}*\nu$ (m^2/s)	θ_1 (s)	θ_{2-5} (s)	G_1 (s^{-1})	G_2 (s^{-1})	G_3 (s^{-1})	G_4 (s^{-1})	G_5 (s^{-1})	G_{AVE} (s^{-1})
0	0.340	-	-	0.8039	100.7	215.8	18.9	9.2	13.0	13.0	-	13.5
30	0.340	-	-	0.7870	100.7	215.8	38.2	29.3	18.5	18.5	-	26.1
60	0.340	-	-	0.7870	100.7	215.8	33.0	26.2	18.5	22.7	-	25.1
90	0.341	-	-	0.7789	100.7	215.8	33.2	29.4	26.3	18.6	-	26.9
120	0.341	-	-	0.7740	100.7	215.8	27.2	29.5	29.5	18.7	-	26.2
150	0.341	-	-	0.7740	100.7	215.8	38.4	29.5	29.5	22.8	-	30.1
180	0.341	-	-	0.7708	100.7	215.8	38.5	29.6	29.6	22.9	-	30.1
240	0.341	-	-	0.7708	100.7	215.8	43.1	32.4	32.4	26.4	-	33.6
300	0.341	-	-	0.7708	100.7	215.8	43.1	32.4	32.4	26.4	-	33.6
360	0.341	-	-	0.7708	100.7	215.8	43.1	32.4	32.4	26.4	-	33.6

Conditions: Hydraulic rate = 2.5 m^3/m^2-h, Dose of PACl = 10 mg/L

: Media size = 3 mm, Media depth = 60 cm

Appendix Table D2 Experimental data of run no.2

Time (min)	Tb (NTU)	pH	Temp (^0C)	Bed Expansion (cm)			Δh_1 (m)	Δh_2 (m)	Δh_3 (m)	Δh_4 (m)	Δh_5 (m)	% Tb removal	Max Floc (µm)
				1	2	3							
0	85	7.26	30.5	60.0	-	-	0.20	0.10	0.20	0.10	0.10	-	-
30	12	7.16	31.5	60.0	-	-	0.20	0.10	0.20	0.10	0.20	86.7	70
60	4	7.14	32.0	60.0	-	-	0.10	0.20	0.20	0.20	0.10	95.2	123
90	4	7.13	32.0	60.0	-	-	0.20	0.20	0.20	0.10	0.20	95.2	265
120	3	7.09	32.0	60.0	-	-	0.20	0.20	0.20	0.20	0.10	95.2	297
150	3	7.15	32.0	60.0	-	-	0.20	0.30	0.20	0.20	0.10	96.4	361
180	2	7.11	32.0	60.0	-	-	0.30	0.30	0.30	0.10	0.10	96.4	475
240	3	7.07	32.5	60.0	-	-	0.30	0.40	0.30	0.10	0.10	96.4	559
300	4	7.08	32.5	60.1	-	-	0.30	0.40	0.30	0.10	0.10	96.4	641
360	4	7.16	32.5	60.1	-	-	0.30	0.40	0.30	0.10	0.10	96.4	749

Time (min)	Porosity of media (f)			$10^{-6}*\nu$ (m^2/s)	θ_1 (s)	θ_{2-5} (s)	G_1 (s^{-1})	G_2 (s^{-1})	G_3 (s^{-1})	G_4 (s^{-1})	G_5 (s^{-1})	G_{AVE} (s^{-1})
	Top layer	Medium layer	Bottom layer									
0	0.340	-	-	0.7955	100.7	215.8	26.8	13.0	18.4	13.0	13.0	16.9
30	0.340	-	-	0.7789	100.7	215.8	27.1	13.2	18.6	13.2	18.6	18.1
60	0.340	-	-	0.7708	100.7	215.8	19.3	18.7	18.7	18.7	13.2	17.7
90	0.340	-	-	0.7708	100.7	215.8	27.3	18.7	18.7	13.2	18.7	19.3
120	0.340	-	-	0.7708	100.7	215.8	27.3	18.7	18.7	18.7	13.2	19.3
150	0.340	-	-	0.7708	100.7	215.8	27.3	22.9	18.7	18.7	13.2	20.2
180	0.340	-	-	0.7708	100.7	215.8	33.4	22.9	22.9	13.2	13.2	21.1
240	0.340	-	-	0.7630	100.7	215.8	33.6	26.6	23.0	13.3	13.3	22.0
300	0.341	-	-	0.7630	100.7	215.8	33.5	26.6	23.0	13.3	13.3	21.9
360	0.341	-	-	0.7630	100.7	215.8	33.5	26.6	23.0	13.3	13.3	21.9

Conditions: Hydraulic rate = 2.5 m^3/m^2-h, Dose of PACl = 5 mg/L

: Media size = 3 mm, Media depth = 60 cm

<u>Appendix Table D3</u> Experimental data of run no.3

Time (min)	Tb (NTU)	pH	Temp (^{0}C)	Bed Expansion (cm) 1	2	3	Δh_1 (m)	Δh_2 (m)	Δh_3 (m)	Δh_4 (m)	Δh_5 (m)	% Tb removal	Max Floc (μm)
0	83	6.98	31	60.00	-	-	0.10	0.10	0.20	0.10	0.00	-	-
30	11	7.06	31.2	60.00	-	-	0.10	0.20	0.20	0.10	0.00	86.7	45
60	4	6.96	31.5	60.05	-	-	0.20	0.20	0.20	0.10	0.00	95.2	112
90	4	7.11	31.5	60.05	-	-	0.20	0.20	0.20	0.15	0.00	95.2	198
120	4	7.09	31.8	60.05	-	-	0.20	0.20	0.20	0.20	0.00	95.2	216
150	3	7.16	31.8	60.05	-	-	0.20	0.20	0.20	0.20	0.00	96.4	324
180	3	7.18	32	60.05	-	-	0.20	0.20	0.20	0.20	0.00	96.4	348
240	3	7.25	32	60.10	-	-	0.35	0.25	0.25	0.10	0.05	96.4	496
300	3	7.26	32.5	60.10	-	-	0.35	0.25	0.25	0.10	0.05	96.4	535
360	3	7.22	32.5	60.10	-	-	0.35	0.25	0.25	0.10	0.05	96.4	678
420	3	7.18	32.5	60.10	-	-	0.35	0.25	0.25	0.10	0.05	96.4	686
480	3	7.23	32.5	60.10	-	-	0.35	0.25	0.25	0.10	0.05	96.4	690

Time (min)	Porosity of media (f) Top layer	Medium layer	Bottom layer	$10^{-6}*\nu$ (m^2/s)	θ_1 (s)	θ_{2-5} (s)	G_1 (s^{-1})	G_2 (s^{-1})	G_3 (s^{-1})	G_4 (s^{-1})	G_5 (s^{-1})	G_{AVE} (s^{-1})
0	0.340	-	-	0.7870	100.7	215.8	19.1	13.1	18.5	13.1	0.0	15.9
30	0.340	-	-	0.7838	100.7	215.8	19.1	18.6	18.6	13.1	0.0	17.3
60	0.340	-	-	0.7789	100.7	215.8	27.1	18.6	18.6	13.2	0.0	19.4
90	0.340	-	-	0.7789	100.7	215.8	27.1	18.6	18.6	16.1	0.0	20.1
120	0.340	-	-	0.7740	100.7	215.8	27.2	18.7	18.7	18.7	0.0	20.8
150	0.340	-	-	0.7740	100.7	215.8	27.2	18.7	18.7	18.7	0.0	20.8
180	0.340	-	-	0.7708	100.7	215.8	27.3	18.7	18.7	18.7	0.0	20.8
240	0.341	-	-	0.7708	100.7	215.8	36.0	20.9	20.9	13.2	9.3	20.1
300	0.341	-	-	0.7630	100.7	215.8	36.2	21.0	21.0	13.3	9.4	20.2
360	0.341	-	-	0.7630	100.7	215.8	36.2	21.0	21.0	13.3	9.4	20.2
420	0.341	-	-	0.7630	100.7	215.8	36.2	21.0	21.0	13.3	9.4	20.2
480	0.341	-	-	0.7630	100.7	215.8	36.2	21.0	21.0	13.3	9.4	20.2

Conditions: Hydraulic rate = 2.5 m^3/m^2-h, Dose of PACl = 2.5 mg/L

: Media size = 3 mm, Media depth = 60 cm

Appendix Table D4 Experimental data of run no.4

Time (min)	Tb (NTU)	pH	Temp (^{0}C)	Bed Expansion (cm) 1	2	3	Δh_1 (m)	Δh_2 (m)	Δh_3 (m)	Δh_4 (m)	Δh_5 (m)	% Tb removal	Max Floc (μm)
0	81	7.43	29.5	60.0	-	-	0.20	0.40	0.50	0.40	0.30	-	-
30	6	7.23	29.5	60.0	-	-	0.40	0.50	0.50	0.50	0.25	92.6	53
60	11	7.25	30.0	60.0	-	-	0.40	0.70	0.80	0.60	0.25	86.4	97
90	22	7.26	31.0	60.2	-	-	0.60	1.00	0.80	0.60	0.45	72.8	136
120	24	7.22	31.0	60.2	-	-	0.60	1.30	1.00	0.70	0.50	70.4	174
150	29	7.19	31.0	60.2	-	-	1.00	1.20	1.10	1.10	0.40	64.2	275
180	30	7.24	31.0	60.2	-	-	0.80	1.50	1.20	1.10	0.40	63.0	307
240	30	7.23	31.5	60.2	-	-	0.80	1.70	1.50	1.20	0.40	63.0	363
300	31	7.27	32.0	60.2	-	-	1.00	2.00	1.70	1.10	0.50	61.7	411
360	29	7.22	32.0	60.2	-	-	0.70	2.20	2.00	1.10	0.50	64.2	476

Time (min)	Porosity of media (f) Top layer	Medium layer	Bottom layer	$10^{-6}*\nu$ (m^2/s)	θ_1 (s)	θ_{2-5} (s)	G_1 (s^{-1})	G_2 (s^{-1})	G_3 (s^{-1})	G_4 (s^{-1})	G_5 (s^{-1})	G_{AVE} (s^{-1})
0	0.340	-	-	0.8127	50.4	108.0	37.5	36.3	40.5	36.3	31.4	36.4
30	0.340	-	-	0.8127	50.4	108.0	53.1	40.5	40.5	40.5	28.7	40.7
60	0.340	-	-	0.8039	50.4	108.0	53.4	48.2	51.6	44.6	28.8	45.3
90	0.341	-	-	0.7870	50.4	108.0	65.9	58.2	52.0	45.0	39.0	52.0
120	0.341	-	-	0.7870	50.4	108.0	65.9	66.3	58.2	48.7	41.1	56.0
150	0.341	-	-	0.7870	50.4	108.0	85.1	63.7	61.0	61.0	36.8	61.5
180	0.341	-	-	0.7870	50.4	108.0	76.1	71.2	63.7	61.0	36.8	61.8
240	0.341	-	-	0.7789	50.4	108.0	76.5	76.2	71.6	64.0	37.0	65.1
300	0.341	-	-	0.7708	50.4	108.0	83.9	83.1	76.6	61.6	41.6	69.4
360	0.341	-	-	0.7708	50.4	108.0	70.2	87.2	83.1	61.6	41.6	68.7

Conditions: Hydraulic rate = 5 m^3/m^2-h, Dose of PACl = 40 mg/L

: Media size = 3 mm, Media depth = 60 cm

Appendix Table D5 Experimental data of run no.5

Time (min)	Tb (NTU)	pH	Temp (^0C)	Bed Expansion (cm) 1	2	3	Δh_1 (m)	Δh_2 (m)	Δh_3 (m)	Δh_4 (m)	Δh_5 (m)	% Tb removal	Max Floc (µm)
0	84	7.06	31.5	60.0	-	-	0.20	0.20	0.20	0.20	0.15	-	-
30	4	6.92	32.0	60.0	-	-	0.10	0.30	0.20	0.40	0.20	95.2	49
60	4	6.94	32.0	60.1	-	-	0.10	0.30	0.40	0.30	0.20	95.2	104
90	5	6.97	31.5	60.1	-	-	0.20	0.50	0.40	0.30	0.20	94.0	141
120	8	7.01	31.5	60.1	-	-	0.40	0.50	0.50	0.30	0.30	90.5	196
150	11	7.04	31.5	60.1	-	-	0.30	0.80	0.50	0.50	0.20	86.9	277
180	10	7.03	31.9	60.1	-	-	0.40	0.80	0.60	0.50	0.20	88.1	330
240	21	6.98	32.0	60.1	-	-	0.40	1.00	0.60	0.70	0.30	75.0	394
300	22	7.04	32.0	60.1	-	-	0.50	1.50	0.90	0.90	0.20	73.8	462
360	21	7.03	32.0	60.1	-	-	0.70	1.40	1.00	0.90	0.30	75.0	516

Time (min)	Porosity of media (f) Top layer	Medium layer	Bottom layer	$10^{-6}*\nu$ (m^2/s)	θ_1 (s)	θ_{2-5} (s)	G_1 (s^{-1})	G_2 (s^{-1})	G_3 (s^{-1})	G_4 (s^{-1})	G_5 (s^{-1})	G_{AVE} (s^{-1})
0	0.340	-	-	0.7789	50.4	108.0	38.3	26.2	26.2	26.2	22.7	27.9
30	0.340	-	-	0.7708	50.4	108.0	27.2	32.2	26.3	37.2	26.3	29.9
60	0.341	-	-	0.7708	50.4	108.0	27.2	32.2	37.2	32.2	26.3	31.0
90	0.341	-	-	0.7789	50.4	108.0	38.3	41.4	37.0	32.0	26.2	35.0
120	0.341	-	-	0.7789	50.4	108.0	54.2	41.4	41.4	32.0	32.0	40.2
150	0.341	-	-	0.7789	50.4	108.0	46.9	52.3	41.4	41.4	26.2	41.6
180	0.341	-	-	0.7724	50.4	108.0	54.4	52.5	45.5	41.5	26.3	44.1
240	0.341	-	-	0.7708	50.4	108.0	54.4	58.8	45.6	49.2	32.2	48.0
300	0.341	-	-	0.7708	50.4	108.0	60.9	72.0	55.8	55.8	26.3	54.2
360	0.341	-	-	0.7708	50.4	108.0	71.7	69.6	58.8	55.8	32.2	57.6

Conditions: Hydraulic rate = 5 m^3/m^2-h , Dose of PACl = 10 mg/L

: Media size = 3 mm, Media depth = 60 cm

Appendix Table D6 Experimental data of run no.6

Time (min)	Tb (NTU)	pH	Temp (^0C)	Bed Expansion (cm) 1	2	3	Δh_1 (m)	Δh_2 (m)	Δh_3 (m)	Δh_4 (m)	Δh_5 (m)	% Tb removal	Max Floc (µm)
0	81	7.05	32.0	60.0	-	-	0.10	0.10	0.30	0.20	0.20	-	-
30	4	7.09	32.0	60.0	-	-	0.10	0.40	0.20	0.20	0.20	95.1	44
60	2	7.11	32.8	60.0	-	-	0.20	0.40	0.20	0.30	0.20	97.5	102
90	4	7.16	32.5	60.0	-	-	0.30	0.60	0.30	0.30	0.10	95.1	156
120	4	7.14	33.0	60.0	-	-	0.40	0.50	0.30	0.40	0.10	95.1	244
150	4	7.17	33.2	60.0	-	-	0.40	0.70	0.70	0.00	0.10	95.1	311
180	5	7.14	33.0	60.0	-	-	0.60	0.60	0.70	0.20	0.30	93.8	404
240	15	7.15	33.5	60.1	-	-	0.50	1.00	0.70	0.50	0.20	81.5	413
300	15	7.11	33.5	60.1	-	-	0.60	1.20	0.80	0.50	0.50	81.5	458
360	16	7.13	33.5	60.1	-	-	0.80	1.30	1.00	0.80	0.30	80.2	477

Time (min)	Porosity of media (f) Top layer	Medium layer	Bottom layer	$10^{-6}*\nu$ (m^2/s)	θ_1 (s)	θ_{2-5} (s)	G_1 (s^{-1})	G_2 (s^{-1})	G_3 (s^{-1})	G_4 (s^{-1})	G_5 (s^{-1})	G_{AVE} (s^{-1})
0	0.340	-	-	0.7708	50.4	108.0	27.2	18.6	32.2	26.3	26.3	26.1
30	0.340	-	-	0.7708	50.4	108.0	27.2	37.2	26.3	26.3	26.3	28.7
60	0.340	-	-	0.7582	50.4	108.0	38.9	37.5	26.5	32.5	26.5	32.4
90	0.340	-	-	0.7630	50.4	108.0	47.4	45.8	32.4	32.4	18.7	35.4
120	0.340	-	-	0.7551	50.4	108.0	55.1	42.1	32.6	37.6	18.8	37.2
150	0.340	-	-	0.7520	50.4	108.0	55.2	49.9	49.9	0.0	18.8	34.7
180	0.340	-	-	0.7551	50.4	108.0	67.4	46.1	49.8	26.6	32.6	44.5
240	0.341	-	-	0.7475	50.4	108.0	61.8	59.7	50.0	42.2	26.7	48.1
300	0.341	-	-	0.7475	50.4	108.0	67.7	65.4	53.4	42.2	42.2	54.2
360	0.341	-	-	0.7475	50.4	108.0	78.2	68.1	59.7	53.4	32.7	58.4

Conditions: Hydraulic rate = 5 m^3/m^2-h, Dose of PACl = 5 mg/L

: Media size = 3 mm, Media depth = 60 cm

Appendix Table D7 Experimental data of run no.7

Time (min)	Tb (NTU)	pH	Temp (^{0}C)	Bed Expansion (cm) 1	2	3	Δh_1 (m)	Δh_2 (m)	Δh_3 (m)	Δh_4 (m)	Δh_5 (m)	% Tb removal	Max Floc (µm)
0	82	7.23	30.5	60.0	-	-	0.20	0.10	0.10	0.30	0.20	-	-
30	5	7.39	30.5	60.0	-	-	0.20	0.20	0.30	0.20	0.20	93.9	52
60	5	7.41	32.8	60.0	-	-	0.20	0.40	0.40	0.30	0.10	93.9	97
90	5	7.36	32.8	60.0	-	-	0.30	0.30	0.50	0.20	0.10	93.9	144
120	5	7.32	32.8	60.0	-	-	0.30	0.40	0.40	0.20	0.20	93.9	202
150	14	7.35	32.5	60.1	-	-	0.30	0.50	0.30	0.30	0.30	82.9	263
180	6	7.38	32.0	60.1	-	-	0.40	0.50	0.50	0.40	0.20	92.7	345
240	5	7.39	33.0	60.1	-	-	0.30	0.70	0.30	0.60	0.20	93.9	384
300	8	7.42	33.1	60.1	-	-	0.50	0.70	0.60	0.30	0.30	90.2	467
360	8	7.45	33.1	60.1	-	-	0.50	0.75	0.75	0.40	0.30	90.2	486
420	8	7.38	33.1	60.1			0.60	0.90	0.70	0.60	0.10	90.2	563
480	8	7.33	33.5	60.1			0.50	1.10	0.70	0.55	0.25	90.2	539
540	8	7.31	33.0	60.1			0.60	1.00	0.80	0.50	0.20	90.2	547

Time (min)	Porosity of media (f) Top layer	Medium layer	Bottom layer	$10^{-6}*\nu$ (m^2/s)	θ_1 (s)	θ_{2-5} (s)	G_1 (s^{-1})	G_2 (s^{-1})	G_3 (s^{-1})	G_4 (s^{-1})	G_5 (s^{-1})	G_{AVE} (s^{-1})
0	0.340	-	-	0.7955	50.4	108.0	37.9	18.3	18.3	31.7	25.9	26.4
30	0.340	-	-	0.7955	50.4	108.0	37.9	25.9	31.7	25.9	25.9	29.5
60	0.340	-	-	0.7582	50.4	108.0	38.9	37.5	37.5	32.5	18.8	33.0
90	0.340	-	-	0.7582	50.4	108.0	47.6	32.5	42.0	26.5	18.8	33.5
120	0.340	-	-	0.7582	50.4	108.0	47.6	37.5	37.5	26.5	26.5	35.1
150	0.341	-	-	0.7630	50.4	108.0	47.4	41.8	32.4	32.4	32.4	37.3
180	0.341	-	-	0.7708	50.4	108.0	54.4	41.6	41.6	37.2	26.3	40.2
240	0.341	-	-	0.7551	50.4	108.0	47.6	49.7	32.5	46.0	26.6	40.5
300	0.341	-	-	0.7536	50.4	108.0	61.6	49.8	46.1	32.6	32.6	44.5
360	0.341	-	-	0.7536	50.4	108.0	61.6	51.5	51.5	37.6	32.6	47.0
420	0.341	-	-	0.7536	50.4	108.0	67.4	56.4	49.8	46.07	18.8	47.7
480	0.341	-	-	0.7475	50.4	108.0	61.8	62.6	50	44.29	29.9	49.7
540	0.341	-	-	0.7551	50.4	108.0	67.4	59.4	53.1	42.02	26.6	49.7

Conditions: Hydraulic rate = 5 m^3/m^2-h, Dose of PACl = 2.5 mg/L

: Media size = 3 mm, Media depth = 60 cm

Appendix Table D8 Experimental data of run no.8

Time (min)	Tb (NTU)	pH	Temp (^{0}C)	Bed Expansion (cm)			Δh_1 (m)	Δh_2 (m)	Δh_3 (m)	Δh_4 (m)	Δh_5 (m)	% Tb removal	Max Floc (μm)
				1	2	3							
0	81	7.38	30.0	60.0	-	-	0.10	0.30	0.20	0.30	0.10	-	-
60	11	7.32	31.5	60.0	-	-	0.10	0.30	0.30	0.30	0.20	86.1	78
120	9	7.29	32.0	60.0	-	-	0.10	0.40	0.30	0.30	0.10	88.6	133
180	9	7.26	32.0	60.0	-	-	0.10	0.50	0.40	0.30	0.20	88.6	236
240	10	7.24	32.0	60.0	-	-	0.20	0.50	0.40	0.40	0.10	87.3	281
300	10	7.21	31.5	60.0	-	-	0.20	0.50	0.50	0.40	0.10	87.3	307
360	11	7.25	31.5	60.0	-	-	0.20	0.60	0.50	0.50	0.30	86.1	334
420	10	7.27	31.0	60.0	-	-	0.30	0.40	0.40	0.50	0.20	88.0	344
480	12	7.33	31.2	60.0	-	-	0.20	0.50	0.40	0.70	0.20	85.5	356
540	10	7.31	31.5	60.0	-	-	0.20	0.60	0.50	0.60	0.20	88.0	354
600	11	7.35	32.0	60.1	-	-	0.20	0.70	0.40	0.80	0.20	86.7	366
660	15	7.29	32.0	60.1	-	-	0.30	0.80	0.50	0.80	0.20	81.9	362
720	17	7.22	32.0	60.1	-	-	0.30	0.90	0.60	0.80	0.30	79.5	365
780	16	7.24	32.8	60.1	-	-	0.30	1.00	0.80	0.80	0.30	80.7	368
840	14	7.25	31.0	60.1	-	-	0.40	0.90	0.60	0.60	0.30	83.1	378
900	15	7.27	31.2	60.1	-	-	0.40	0.90	0.60	0.80	0.30	81.9	372
960	16	7.22	31.5	60.1	-	-	0.40	1.00	0.70	0.80	0.40	80.7	380
1020	19	7.21	32.0	60.1	-	-	0.60	1.10	0.70	0.70	0.30	77.1	376
1080	37	7.19	32.0	60.2	-	-	0.60	1.10	1.00	0.80	0.20	55.4	373
1140	15	7.26	32.0	60.2	-	-	0.60	1.30	0.90	0.80	0.30	81.9	383
1200	18	7.22	32.2	60.2	-	-	0.60	1.40	0.90	0.90	0.30	78.3	379
1260	14	7.29	32.5	60.2	-	-	0.60	1.40	1.10	0.90	0.10	83.1	387
1320	17	7.33	32.5	60.2	-	-	0.70	1.50	1.20	0.90	0.20	79.5	389
1380	13	7.30	32.0	60.2	-	-	0.80	1.60	1.10	1.10	0.30	84.3	385
1440	17	7.28	31.5	60.2	-	-	0.90	1.70	1.20	0.90	0.50	79.5	382

Appendix Table D8 (Cont'd)

Time (min)	Porosity of media (f) Top layer	Medium layer	Bottom layer	$10^{-6}*\nu$ (m^2/s)	θ_1 (s)	θ_{2-5} (s)	G_1 (s^{-1})	G_2 (s^{-1})	G_3 (s^{-1})	G_4 (s^{-1})	G_5 (s^{-1})	G_{AVE} (s^{-1})
0	0.340	-	-	0.8039	50.4	108.0	26.7	31.6	25.8	31.6	18.2	26.8
60	0.340	-	-	0.7789	50.4	108.0	27.1	32.1	32.1	32.1	26.2	29.9
120	0.340	-	-	0.7708	50.4	108.0	27.2	37.2	32.2	32.2	18.6	29.5
180	0.340	-	-	0.7708	50.4	108.0	27.2	41.6	37.2	32.2	26.3	32.9
240	0.340	-	-	0.7708	50.4	108.0	38.5	41.6	37.2	37.2	18.6	34.6
300	0.340	-	-	0.7789	50.4	108.0	38.3	41.4	41.4	37.0	18.5	35.3
360	0.340	-	-	0.7789	50.4	108.0	38.3	45.4	41.4	41.4	32.1	39.7
420	0.340	-	-	0.7870	50.4	108.0	46.7	36.8	36.8	41.2	26.1	37.5
480	0.340	-	-	0.7838	50.4	108.0	38.2	41.3	36.9	48.8	26.1	38.3
540	0.340	-	-	0.7789	50.4	108.0	38.3	45.4	41.4	45.4	26.2	39.3
600	0.341	-	-	0.7708	50.4	108.0	38.5	49.2	37.2	52.6	26.3	40.8
660	0.341	-	-	0.7708	50.4	108.0	47.2	52.6	41.6	52.6	26.3	44.0
720	0.341	-	-	0.7708	50.4	108.0	47.2	55.8	45.6	52.6	32.2	46.7
780	0.341	-	-	0.7582	50.4	108.0	47.5	59.3	53.0	53.0	32.5	49.1
840	0.341	-	-	0.7870	50.4	108.0	53.9	55.2	45.1	45.1	31.9	46.2
900	0.341	-	-	0.7838	50.4	108.0	54.0	55.3	45.2	52.2	31.9	47.7
960	0.341	-	-	0.7789	50.4	108.0	54.2	58.5	48.9	52.3	37.0	50.2
1020	0.341	-	-	0.7708	50.4	108.0	66.7	61.7	49.2	49.2	32.2	51.8
1080	0.341	-	-	0.7708	50.4	108.0	66.6	61.6	58.8	52.6	26.3	53.2
1140	0.341	-	-	0.7708	50.4	108.0	66.6	67.0	55.7	52.6	32.2	54.8
1200	0.341	-	-	0.7692	50.4	108.0	66.7	69.6	55.8	55.8	32.2	56.0
1260	0.341	-	-	0.7630	50.4	108.0	67.0	69.9	61.9	56.0	18.7	54.7
1320	0.341	-	-	0.7630	50.4	108.0	72.3	72.3	64.7	56.0	26.4	58.4
1380	0.341	-	-	0.7708	50.4	108.0	76.9	74.3	61.6	61.6	32.2	61.3
1440	0.341	-	-	0.7789	50.4	108.0	81.2	76.2	64.0	55.5	41.3	63.6

Conditions: Hydraulic rate = 5 m^3/m^2-h, Dose of PACl = 1.25 mg/L

: Media size = 3 mm, Media depth = 60 cm

Appendix Table D9 Experimental data of run no.9

Time (min)	Tb (NTU)	pH	Temp (^{0}C)	Bed Expansion (cm) 1	2	3	Δh_1 (m)	Δh_2 (m)	Δh_3 (m)	Δh_4 (m)	Δh_5 (m)	% Tb removal	Max Floc (µm)
0	83	6.97	30.0	60.0	-	-	0.20	0.50	0.40	0.40	0.30	-	-
30	19	7.41	31.0	60.0	-	-	0.40	0.70	0.60	1.60	0.80	77.1	0
60	26	7.43	31.2	60.0	-	-	0.50	1.40	1.20	0.80	1.30	68.7	0
90	32	7.38	31.2	60.0	-	-	0.70	1.70	0.90	1.80	0.60	61.4	62
120	35	7.36	31.2	60.0	-	-	0.50	2.00	1.40	0.60	0.90	57.8	101
150	37	7.38	31.5	60.0	-	-	0.50	1.90	1.40	0.90	0.70	55.4	143
180	34	7.35	31.5	60.2	-	-	0.50	2.00	1.40	0.90	0.70	59.0	195
240	41	7.28	31.5	60.2	-	-	0.50	2.40	1.20	0.50	0.70	50.6	214
300	54	7.27	31.5	60.4	-	-	0.20	2.10	0.30	0.70	0.80	34.9	248
360	56	7.31	32.0	60.5	-	-	0.50	2.10	0.50	0.60	0.70	32.5	275

Time (min)	Porosity of media (f) Top layer	Medium layer	Bottom layer	$10^{-6}*\nu$ (m^2/s)	θ_1 (s)	θ_{2-5} (s)	G_1 (S^{-1})	G_2 (S^{-1})	G_3 (S^{-1})	G_4 (S^{-1})	G_5 (S^{-1})	G_{AVE} (S^{-1})
0	0.340	-	-	0.8039	25.2	53.9	53.4	57.7	51.6	51.6	44.7	51.8
30	0.340	-	-	0.7870	25.2	53.9	76.4	69.0	63.9	104.3	73.8	77.5
60	0.340	-	-	0.7838	25.2	53.9	85.5	97.8	90.5	73.9	94.2	88.4
90	0.340	-	-	0.7838	25.2	53.9	101.2	107.8	78.4	110.9	64.0	92.5
120	0.340	-	-	0.7838	25.2	53.9	85.5	116.9	97.8	64.0	78.4	88.5
150	0.340	-	-	0.7789	25.2	53.9	85.8	114.3	98.1	78.6	69.4	89.2
180	0.341	-	-	0.7789	25.2	53.9	85.7	117.0	97.9	78.5	69.2	89.7
240	0.341	-	-	0.7789	25.2	53.9	85.7	128.2	90.7	58.5	69.2	86.5
300	0.342	-	-	0.7789	25.2	53.9	54.1	119.7	45.3	69.1	73.9	72.4
360	0.343	-	-	0.7708	25.2	53.9	85.9	120.3	58.7	64.3	69.4	79.7

Conditions: Hydraulic rate = 10 m^3/m^2-h, Dose of PACl = 40 mg/L

: Media size = 3 mm, Media depth = 60 cm

Appendix Table D10 Experimental data of run no.10

Time (min)	Tb (NTU)	pH	Temp (^{0}C)	Bed Expansion (cm.) 1	2	3	Δh_1 (m)	Δh_2 (m)	Δh_3 (m)	Δh_4 (m)	Δh_5 (m)	% Tb removal	Max .Floc (μm)
0	79	7.45	33.0	60.0	-	-	0.30	0.30	0.40	0.60	0.30	-	-
30	12	7.32	32.8	60.0	-	-	0.20	0.60	0.50	0.40	0.50	84.8	45
60	16	7.36	32.8	60.0	-	-	0.30	0.80	0.40	0.50	0.50	79.7	59
90	16	7.37	33.0	60.0	-	-	0.30	1.20	0.70	0.50	0.40	79.7	90
120	16	7.34	32.8	60.1	-	-	0.40	1.30	0.60	0.40	0.60	79.7	109
150	19	7.28	32.8	60.1	-	-	0.40	1.70	0.70	0.60	0.60	75.9	123
180	23	7.25	32.5	60.1	-	-	0.60	2.10	0.60	0.80	0.60	70.9	142
240	29	7.27	32.5	60.1	-	-	0.70	2.00	0.90	0.80	0.70	63.3	236
300	28	7.32	32.8	60.2	-	-	0.60	1.90	1.00	0.80	0.90	64.6	252
360	29	7.34	32.6	60.2	-	-	0.50	1.70	1.00	1.00	1.00	63.3	327

Time (min)	Porosity of media (f) Top layer	Medium layer	Bottom layer	$10^{-6}*\nu$ (m^2/s)	θ_1 (s)	θ_{2-5} (s)	G_1 (s^{-1})	G_2 (s^{-1})	G_3 (s^{-1})	G_4 (s^{-1})	G_5 (s^{-1})	G_{AVE} (s^{-1})
0	0.340	-	-	0.7551	25.2	53.9	67.5	46.1	53.3	65.2	46.1	55.6
30	0.340	-	-	0.7582	25.2	53.9	55.0	65.1	59.4	53.1	59.4	58.4
60	0.340	-	-	0.7582	25.2	53.9	67.4	75.2	53.1	59.4	59.4	62.9
90	0.340	-	-	0.7551	25.2	53.9	67.5	92.2	70.4	59.5	53.3	68.6
120	0.341	-	-	0.7582	25.2	53.9	77.7	95.7	65.0	53.1	65.0	71.3
150	0.341	-	-	0.7582	25.2	53.9	77.7	109.5	70.2	65.0	65.0	77.5
180	0.341	-	-	0.7630	25.2	53.9	94.9	121.3	64.8	74.9	64.8	84.1
240	0.341	-	-	0.7630	25.2	53.9	102.5	118.4	79.4	74.9	70.0	89.0
300	0.341	-	-	0.7582	25.2	53.9	95.1	115.6	83.9	75.0	79.6	89.8
360	0.341	-	-	0.7614	25.2	53.9	86.6	109.1	83.7	83.7	83.7	89.4

Conditions: Hydraulic rate = 10 m^3/m^2-h, Dose of PACl = 10 mg/L

: Media size = 3 mm, Media depth = 60 cm

Appendix Table D11 Experimental data of run no.11

Time (min)	Tb (NTU)	pH	Temp (^{0}C)	Bed Expansion (cm.) 1	2	3	Δh_1 (m)	Δh_2 (m)	Δh_3 (m)	Δh_4 (m)	Δh_5 (m)	% Tb removal	Max .Floc (µm)
0	82	6.92	31.0	60.0	-	-	0.10	0.60	0.40	0.40	0.20	-	-
30	7	6.98	32.0	60.0	-	-	0.30	0.60	0.50	0.50	0.20	91.5	49
60	9	7.04	32.0	60.0	-	-	0.40	0.90	0.70	0.50	0.30	89.0	74
90	15	7.03	32.1	60.0	-	-	0.50	1.20	0.80	0.50	0.30	81.7	107
120	18	7.05	32.5	60.0	-	-	0.50	1.30	0.80	0.50	0.20	78.0	132
150	22	7.08	32.5	60.0	-	-	0.60	1.40	0.90	0.60	0.50	73.2	193
180	25	7.11	32.5	60.0	-	-	0.80	1.50	0.90	0.70	0.70	69.5	247
240	28	7.14	32.8	60.2	-	-	0.70	1.80	0.90	0.50	0.60	65.9	271
300	29	7.17	32.8	60.2	-	-	0.60	1.80	0.90	0.60	0.70	64.6	326
360	28	7.15	32.8	60.2	-	-	0.40	1.80	0.90	0.60	1.20	65.9	373

Time (min)	Porosity of media (f) Top layer	Medium layer	Bottom layer	$10^{-6}*\nu$ (m^2/s)	θ_1 (s)	θ_{2-5} (s)	G_1 (s^{-1})	G_2 (s^{-1})	G_3 (s^{-1})	G_4 (s^{-1})	G_5 (s^{-1})	G_{AVE} (s^{-1})
0	0.340	-	-	0.7870	25.2	53.9	38.2	63.9	52.2	52.2	36.9	48.7
30	0.340	-	-	0.7708	25.2	53.9	66.8	64.6	58.9	58.9	37.3	57.3
60	0.340	-	-	0.7708	25.2	53.9	77.2	79.1	69.7	58.9	45.6	66.1
90	0.340	-	-	0.7692	25.2	53.9	86.3	91.4	74.6	59.0	45.7	71.4
120	0.340	-	-	0.7630	25.2	53.9	86.7	95.5	74.9	59.2	37.5	70.8
150	0.340	-	-	0.7630	25.2	53.9	95.0	99.1	79.5	64.9	59.2	79.5
180	0.340	-	-	0.7630	25.2	53.9	109.7	102.6	79.5	70.1	70.1	86.4
240	0.341	-	-	0.7582	25.2	53.9	102.7	112.5	79.6	59.3	65.0	83.8
300	0.341	-	-	0.7582	25.2	53.9	95.1	112.5	79.6	65.0	70.2	84.5
360	0.341	-	-	0.7582	25.2	53.9	77.7	112.5	79.6	65.0	91.9	85.3

Conditions: Hydraulic rate = m^3/m^2-h, Dose of PACl = 5 mg/L

: Media size = 3 mm, Media depth = 60 cm

Appendix Table D12 Experimental data of run no.12

Time (min)	Tb (NTU)	pH	Temp (^0C)	Bed Expansion (cm) 1	2	3	Δh_1 (m)	Δh_2 (m)	Δh_3 (m)	Δh_4 (m)	Δh_5 (m)	% Tb removal	Max Floc (μm)
0	79	7.31	31.0	60.0	-	-	0.20	0.70	0.60	0.70	0.20	-	-
30	17	7.18	32.0	60.0	-	-	0.40	0.80	0.70	0.80	0.30	78.5	67
60	11	7.24	32.0	60.0	-	-	0.50	0.70	0.70	0.70	0.40	86.1	92
90	11	7.29	32.2	60.0	-	-	0.40	0.70	0.80	0.80	0.40	86.1	132
120	13	7.25	32.5	60.0	-	-	0.30	0.90	0.80	0.80	0.30	83.5	195
150	13	7.23	33.0	60.0	-	-	0.50	0.90	0.90	0.80	0.40	83.5	233
180	13	7.17	32.8	60.0	-	-	0.40	1.10	1.10	0.80	0.40	83.5	272
240	17	7.22	33.0	60.0	-	-	0.60	1.60	1.20	1.10	0.40	78.5	357
300	21	7.26	32.8	60.2	-	-	0.60	1.40	1.20	1.20	0.50	73.4	384
360	21	7.23	30.0	60.2	-	-	0.50	1.50	1.40	1.10	0.70	73.4	406
420	22	7.25	31.0	60.6	-	-	0.40	1.30	1.30	1.10	0.80	72.2	413

Time (min)	Porosity of media (f) Top layer	Medium layer	Bottom layer	$10^{-6}*\nu$ (m^2/s)	θ_1 (s)	θ_{2-5} (s)	G_1 (s^{-1})	G_2 (s^{-1})	G_3 (s^{-1})	G_4 (s^{-1})	G_5 (s^{-1})	G_{AVE} (s^{-1})
0	0.340	-	-	0.7870	25.2	53.9	54.0	69.0	63.9	69.0	36.9	58.6
30	0.340	-	-	0.7708	25.2	53.9	77.2	74.5	69.7	74.5	45.6	68.3
60	0.340	-	-	0.7708	25.2	53.9	86.3	69.7	69.7	69.7	52.7	69.6
90	0.340	-	-	0.7692	25.2	53.9	77.2	69.8	74.6	74.6	52.8	69.8
120	0.340	-	-	0.7630	25.2	53.9	67.2	79.5	74.9	74.9	45.9	68.5
150	0.340	-	-	0.7551	25.2	53.9	87.2	79.9	79.9	75.3	53.3	75.1
180	0.340	-	-	0.7582	25.2	53.9	77.8	88.1	88.1	75.2	53.1	76.5
240	0.340	-	-	0.7551	25.2	53.9	95.5	106.5	92.2	88.3	53.3	87.2
300	0.341	-	-	0.7582	25.2	53.9	95.1	99.3	91.9	91.9	59.3	87.5
360	0.341	-	-	0.8039	25.2	53.9	84.3	99.8	96.4	85.4	68.2	86.8
420	0.343	-	-	0.7870	25.2	53.9	76.0	93.6	93.6	86.1	73.4	84.5

Conditions: Hydraulic rate = 10 m^3/m^2-h, Dose of PACl = 2.5 mg/L

: Media size = 3 mm, Media depth = 60 cm

<u>Appendix Table D13</u> Experimental data of run no.13

Time (min)	Tb (NTU)	pH	Temp (^{0}C)	Bed Expansion (cm)			Δh_1 (m)	Δh_2 (m)	Δh_3 (m)	Δh_4 (m)	Δh_5 (m)	% Tb removal	Max Floc (µm)
				1	2	3							
0	82	7.32	31.0	60.0	-	-	0.10	0.60	0.60	0.50	0.40	-	-
30	28	7.10	31.2	60.0	-	-	0.30	0.50	0.50	0.70	1.20	65.9	42
60	22	7.16	31.0	60.0	-	-	0.30	0.40	0.70	0.40	0.30	73.2	61
90	21	7.14	31.0	60.0	-	-	0.30	0.70	0.60	0.40	0.20	74.4	75
120	29	7.12	31.2	60.2	-	-	0.40	0.70	0.60	0.70	0.30	64.6	106
150	26	7.18	31.5	60.2	-	-	0.30	0.70	0.80	0.70	0.30	68.3	128
180	23	7.23	31.5	60.2	-	-	0.40	0.70	0.70	0.80	0.40	72.0	198
240	26	7.24	31.5	60.2	-	-	0.40	0.90	0.70	0.80	0.40	68.3	255
300	25	7.21	31.5	60.2	-	-	0.40	0.90	0.90	0.90	0.40	69.5	286
360	26	7.24	32.0	60.2	-	-	0.50	0.90	1.00	0.80	0.50	68.3	303

Time (min)	Porosity of media (f)			$10^{-6}*\nu$ (m^2/s)	θ_1 (s)	θ_{2-5} (s)	G_1 (s^{-1})	G_2 (s^{-1})	G_3 (s^{-1})	G_4 (s^{-1})	G_5 (s^{-1})	G_{AVE} (s^{-1})
	Top layer	Medium layer	Bottom layer									
0	0.340	-	-	0.7870	25.2	53.9	38.2	63.9	63.9	58.3	52.2	55.3
30	0.340	-	-	0.7838	25.2	53.9	66.3	58.4	58.4	69.1	90.5	68.6
60	0.340	-	-	0.7870	25.2	53.9	66.1	52.2	69.0	52.2	45.2	56.9
90	0.340	-	-	0.7870	25.2	53.9	66.1	69.0	63.9	52.2	36.9	57.6
120	0.341	-	-	0.7838	25.2	53.9	76.4	69.0	63.9	69.0	45.2	64.7
150	0.341	-	-	0.7789	25.2	53.9	66.4	69.2	74.0	69.2	45.3	64.8
180	0.341	-	-	0.7789	25.2	53.9	76.6	69.2	69.2	74.0	52.3	68.3
240	0.341	-	-	0.7789	25.2	53.9	76.6	78.5	69.2	74.0	52.3	70.2
300	0.341	-	-	0.7789	25.2	53.9	76.6	78.5	78.5	78.5	52.3	72.9
360	0.341	-	-	0.7708	25.2	53.9	86.1	78.9	83.2	74.4	58.8	76.3

Conditions: Hydraulic rate = 10 m^3/m^2-h, Dose of PACl = 1.25 mg/L

: Media size = 3 mm, Media depth = 60 cm

Appendix Table D14 Experimental data of run no.14

Time (min)	Tb (NTU)	pH	Temp (^{0}C)	Bed Expansion (cm) 1	2	3	Δh_1 (m)	Δh_2 (m)	Δh_3 (m)	Δh_4 (m)	Δh_5 (m)	% Tb removal	Max Floc (µm)
0	86	6.98	28.5	30	-	-	0.05	0.05	0.10	-	-	-	-
30	23	7.31	29.2	30	-	-	0.05	0.05	0.05	-	-	73.3	98
60	14	7.26	29.5	30	-	-	0.05	0.05	0.10	-	-	83.7	146
90	11	7.24	30.0	30	-	-	0.10	0.10	0.05	-	-	87.2	223
120	10	7.18	30.5	30	-	-	0.10	0.10	0.05	-	-	88.4	362
150	9	7.15	30.5	30	-	-	0.10	0.10	0.05	-	-	89.5	491
180	12	7.17	31.0	30	-	-	0.05	0.05	0.20	-	-	86.0	690
240	11	7.19	31.0	30	-	-	0.05	0.05	0.20	-	-	87.2	771
300	10	7.23	31.0	30	-	-	0.05	0.05	0.20	-	-	88.4	809
360	10	7.26	31.0	30	-	-	0.05	0.05	0.20	-	-	88.4	855

Time (min)	Porosity of media (f) Top layer	Medium layer	Bottom layer	$10^{-6}*\nu$ (m^2/s)	θ_1 (s)	θ_{2-5} (s)	G_1 (s^{-1})	G_2 (s^{-1})	G_3 (s^{-1})	G_4 (s^{-1})	G_5 (s^{-1})	G_{AVE} (s^{-1})
0	0.360	-	-	0.8304	100.7	215.8	12.8	8.7	12.3	-	-	11.3
30	0.360	-	-	0.8179	100.7	215.8	12.9	8.8	8.8	-	-	10.1
60	0.360	-	-	0.8127	100.7	215.8	12.9	8.8	12.5	-	-	11.4
90	0.360	-	-	0.8039	100.7	215.8	18.3	12.5	8.9	-	-	13.2
120	0.360	-	-	0.7955	100.7	215.8	18.4	12.6	8.9	-	-	13.3
150	0.360	-	-	0.7904	100.7	215.8	18.4	12.6	8.9	-	-	13.3
180	0.360	-	-	0.7870	100.7	215.8	13.1	9.0	17.9	-	-	13.3
240	0.360	-	-	0.7870	100.7	215.8	13.1	9.0	17.9	-	-	13.3
300	0.360	-	-	0.7870	100.7	215.8	13.1	9.0	17.9	-	-	13.3
360	0.360	-	-	0.7870	100.7	215.8	13.1	9.0	17.9	-	-	13.3

Conditions: Hydraulic rate = 2.5 m^3/m^2-h, Dose of PACl = 2.5 mg/L.

: Media size = 6 mm, Media depth = 30 cm

Appendix Table D15 Experimental data of run no.15

Time (min)	Tb (NTU)	pH	Temp (^{0}C)	Bed Expansion (cm) 1	2	3	Δh_1 (m)	Δh_2 (m)	Δh_3 (m)	Δh_4 (m)	Δh_5 (m)	% Tb removal	Max Floc (µm)
0	85	7.12	29.0	60	-	-	0.10	0.10	0.05	0.05	-	-	-
30	13	7.01	29.3	60	-	-	0.10	0.05	0.05	0.05	-	84.7	60
60	10	7.03	29.5	60	-	-	0.10	0.05	0.05	0.05	-	88.2	108
90	8	6.97	30.0	60	-	-	0.10	0.05	0.10	0.10	-	90.6	126
120	7	6.99	30.0	60	-	-	0.10	0.05	0.10	0.10	-	91.8	254
150	8	7.04	30.3	60	-	-	0.10	0.10	0.10	0.10	-	90.6	335
180	7	7.06	30.3	60	-	-	0.10	0.10	0.10	0.10	-	91.8	360
240	8	7.03	30.3	60	-	-	0.10	0.10	0.10	0.10	-	90.6	434
300	7	7.01	30.3	60	-	-	0.10	0.10	0.10	0.10	-	91.8	456
360	7	7.04	30.3	60	-	-	0.10	0.10	0.10	0.10	-	91.8	498

Time (min)	Porosity of media (f) Top layer	Medium layer	Bottom layer	$10^{-6}*\nu$ (m^2/s)	θ_1 (s)	θ_{2-5} (s)	G_1 (s^{-1})	G_2 (s^{-1})	G_3 (s^{-1})	G_4 (s^{-1})	G_5 (s^{-1})	G_{AVE} (s^{-1})
0	0.360	-	-	0.8214	100.7	215.8	18.1	12.4	8.8	8.8	-	12.0
30	0.360	-	-	0.8162	100.7	215.8	18.2	8.8	8.8	8.8	-	11.1
60	0.360	-	-	0.8127	100.7	215.8	18.2	8.8	8.8	8.8	-	11.2
90	0.360	-	-	0.8039	100.7	215.8	18.3	8.9	12.5	12.5	-	13.1
120	0.360	-	-	0.8039	100.7	215.8	18.3	8.9	12.5	12.5	-	13.1
150	0.360	-	-	0.7990	100.7	215.8	18.4	12.6	12.6	12.6	-	14.0
180	0.360	-	-	0.7990	100.7	215.8	18.4	12.6	12.6	12.6	-	14.0
240	0.360	-	-	0.7990	100.7	215.8	18.4	12.6	12.6	12.6	-	14.0
300	0.360	-	-	0.7990	100.7	215.8	18.4	12.6	12.6	12.6	-	14.0
360	0.360	-	-	0.7990	100.7	215.8	18.4	12.6	12.6	12.6	-	14.0

Conditions: Hydraulic rate = 2.5 m^3/m^2-h, Dose of PACl = 2.5 mg/L

: Media size = 6 mm, Media depth = 60 cm

Appendix Table D16 Experimental data of run no.16

Time (min)	Tb (NTU)	pH	Temp (^{0}C)	Bed Expansion (cm) 1	2	3	Δh_1 (m)	Δh_2 (m)	Δh_3 (m)	Δh_4 (m)	Δh_5 (m)	% Tb removal	Max Floc (µm)
0	88	7.45	31.0	30	-	-	0.10	0.10	0.10	0.10	-	-	-
30	15	7.22	30.5	30	-	-	0.10	0.20	0.10	0.10	-	83.0	82
60	12	7.24	30.8	30	-	-	0.10	0.20	0.10	0.10	-	86.4	117
90	8	7.23	31.0	30	-	-	0.10	0.20	0.10	0.10	-	90.9	175
120	6	7.28	31.0	30	-	-	0.10	0.30	0.10	0.10	-	93.2	331
150	6	7.26	31.0	30	-	-	0.30	0.20	0.10	0.10	-	93.2	484
180	6	7.21	31.0	30	-	-	0.40	0.30	0.10	0.10	-	93.2	523
240	6	7.18	31.0	30	-	-	0.40	0.30	0.10	0.10	-	93.2	590
300	5	7.16	31.0	30	-	-	0.40	0.30	0.10	0.10	-	94.3	642
360	5	7.23	31.0	30	-	-	0.40	0.30	0.10	0.10	-	94.3	692

Time (min)	Porosity of media (f) Top layer	Medium layer	Bottom layer	$10^{-6}*\nu$ (m^2/s)	θ_1 (s)	θ_{2-5} (s)	G_1 (s^{-1})	G_2 (s^{-1})	G_3 (s^{-1})	G_4 (s^{-1})	G_5 (s^{-1})	G_{AVE} (s^{-1})
0	0.340	-	-	0.7870	100.7	215.8	19.1	13.0	13.0	13.0	-	14.5
30	0.340	-	-	0.7955	100.7	215.8	19.0	18.3	13.0	13.0	-	15.8
60	0.340	-	-	0.7904	100.7	215.8	19.0	18.4	13.0	13.0	-	15.9
90	0.340	-	-	0.7870	100.7	215.8	19.1	18.4	13.0	13.0	-	15.9
120	0.340	-	-	0.7870	100.7	215.8	19.1	22.6	13.0	13.0	-	16.9
150	0.340	-	-	0.7870	100.7	215.8	33.0	18.4	13.0	13.0	-	19.4
180	0.340	-	-	0.7870	100.7	215.8	38.2	22.6	13.0	13.0	-	21.7
240	0.340	-	-	0.7870	100.7	215.8	38.2	22.6	13.0	13.0	-	21.7
300	0.340	-	-	0.7870	100.7	215.8	38.2	22.6	13.0	13.0	-	21.7
360	0.340	-	-	0.7870	100.7	215.8	38.2	22.6	13.0	13.0	-	21.7

Conditions: Hydraulic rate = 2.5 m^3/m^2-h, Dose of PACl = 2.5 mg/L

: Media size = 3 mm, Media depth = 30 cm

Appendix Table D17 Experimental data of run no.17

Time (min)	Tb (NTU)	pH	Temp (^0C)	Bed Expansion (cm) 1	2	3	Δh_1 (m)	Δh_2 (m)	Δh_3 (m)	Δh_4 (m)	Δh_5 (m)	% Tb removal	Max Floc (µm)
0	81	7.21	29	60	-	-	0.10	0.10	0.20	0.10	0.00	-	-
30	26	7.02	30.8	60	-	-	0.10	0.20	0.20	0.10	0.00	67.9	42
60	5	7.05	31	60	-	-	0.10	0.20	0.20	0.10	0.10	93.8	85
90	5	7.03	31	60	-	-	0.10	0.20	0.20	0.10	0.10	93.8	134
120	4	7.07	31.2	60	-	-	0.10	0.20	0.20	0.10	0.10	95.1	198
150	3	7.06	31.2	60	-	-	0.10	0.20	0.20	0.00	0.20	96.3	253
180	3	7.13	31.8	60	-	-	0.30	0.30	0.20	0.20	0.20	96.3	345
240	3	7.14	31.8	60	-	-	0.30	0.30	0.20	0.20	0.20	96.3	354
300	2	7.16	31.8	60	-	-	0.30	0.30	0.20	0.20	0.20	97.5	457
360	2	7.09	31.8	60	-	-	0.30	0.30	0.20	0.20	0.20	97.5	466

Time (min)	Porosity of media (f) Top layer	Medium layer	Bottom layer	$10^{-6}*\nu$ (m^2/s)	θ_1 (s)	θ_{2-5} (s)	G_1 (s^{-1})	G_2 (s^{-1})	G_3 (s^{-1})	G_4 (s^{-1})	G_5 (s^{-1})	G_{AVE} (s^{-1})
0	0.340	-	-	0.8214	100.7	215.8	18.7	12.8	18.0	12.8	0.0	12.4
30	0.340	-	-	0.7904	100.7	215.8	19.0	18.4	18.4	13.0	0.0	13.8
60	0.340	-	-	0.7870	100.7	215.8	19.1	18.4	18.4	13.0	13.0	16.4
90	0.340	-	-	0.7870	100.7	215.8	19.1	18.4	18.4	13.0	13.0	16.4
120	0.340	-	-	0.7838	100.7	215.8	19.1	18.5	18.5	13.1	13.1	16.4
150	0.340	-	-	0.7838	100.7	215.8	19.1	18.5	18.5	0.0	18.5	14.9
180	0.340	-	-	0.7740	100.7	215.8	33.3	22.8	18.6	18.6	18.6	22.4
240	0.340	-	-	0.7740	100.7	215.8	33.3	22.8	18.6	18.6	18.6	22.4
300	0.340	-	-	0.7740	100.7	215.8	33.3	22.8	18.6	18.6	18.6	22.4
360	0.340	-	-	0.7740	100.7	215.8	33.3	22.8	18.6	18.6	18.6	22.4

Conditions: Hydraulic rate = 2.5 m^3/m^2-h, Dose of PACl = 2.5 mg/L

: Media size = 3 mm, Media depth = 60 cm

Appendix Table D18 Experimental data of run no.18

Time (min)	Tb (NTU)	pH	Temp (^0C)	Bed Expansion (cm) 1	2	3	Δh_1 (m)	Δh_2 (m)	Δh_3 (m)	Δh_4 (m)	Δh_5 (m)	% Tb removal	Max Floc (µm)
0	87	7.03	29.8	30	-	-	0.05	0.05	0.10	-	-	-	-
30	50	7.34	30.0	30	-	-	0.05	0.05	0.05	-	-	42.5	83
60	26	7.35	30.3	30	-	-	0.05	0.05	0.05	-	-	73.5	218
90	26	7.29	30.8	30	-	-	0.05	0.05	0.05	-	-	73.5	497
120	25	7.31	30.8	30	-	-	0.05	0.05	0.05	-	-	74.5	635
150	25	7.33	30.8	30	-	-	0.05	0.05	0.10	-	-	74.5	784
180	21	7.34	31.0	30	-	-	0.05	0.05	0.10	-	-	78.6	987
240	21	7.28	31.0	30	-	-	0.05	0.05	0.10	-	-	78.6	993
300	21	7.26	31.0	30	-	-	0.05	0.05	0.10	-	-	78.6	1063
360	21	7.27	31.0	30	-	-	0.05	0.05	0.10	-	-	78.6	1081

Time (min)	Porosity of media (f) Top layer	Medium layer	Bottom layer	$10^{-6}*\nu$ (m^2/s)	θ_1 (s)	θ_{2-5} (s)	G_1 (s^{-1})	G_2 (s^{-1})	G_3 (s^{-1})	G_4 (s^{-1})	G_5 (s^{-1})	G_{AVE} (s^{-1})
0	0.400	-	-	0.8074	100.7	215.8	12.3	8.4	11.9	-	-	10.8
30	0.400	-	-	0.8039	100.7	215.8	12.3	8.4	8.4	-	-	9.7
60	0.400	-	-	0.7950	100.7	215.8	12.4	8.5	8.5	-	-	9.8
90	0.400	-	-	0.7904	100.7	215.8	12.4	8.5	8.5	-	-	9.8
120	0.400	-	-	0.7904	100.7	215.8	12.4	8.5	8.5	-	-	9.8
150	0.400	-	-	0.7904	100.7	215.8	12.4	8.5	12.0	-	-	11.0
180	0.400	-	-	0.7789	100.7	215.8	12.5	8.5	12.1	-	-	11.0
240	0.400	-	-	0.7789	100.7	215.8	12.5	8.5	12.1	-	-	11.0
300	0.400	-	-	0.7789	100.7	215.8	12.5	8.5	12.1	-	-	11.0
360	0.400	-	-	0.7789	100.7	215.8	12.5	8.5	12.1	-	-	11.0

Conditions: Hydraulic rate = 2.5 m^3/m^2-h, Dose of PACl = 2.5 mg/L

: Media size = 10 mm, Media depth = 30 cm

Appendix Table D19 Experimental data of run no.19

Time (min)	Tb (NTU)	pH	Temp (^0C)	Bed Expansion (cm) 1	2	3	Δh_1 (m)	Δh_2 (m)	Δh_3 (m)	Δh_4 (m)	Δh_5 (m)	% Tb removal	Max Floc (µm)
0	87	7.41	29.5	60	-	-	0.05	0.05	0.10	0.00	0.00	-	-
30	18	7.26	30.5	60	-	-	0.05	0.05	0.10	0.00	0.00	79.3	79
60	14	7.29	31	60	-	-	0.05	0.05	0.10	0.00	0.00	83.9	122
90	13	7.23	31	60	-	-	0.05	0.05	0.10	0.00	0.00	85.1	219
120	12	7.27	31	60	-	-	0.10	0.10	0.10	0.00	0.00	86.2	351
150	12	7.24	31.2	60	-	-	0.10	0.10	0.10	0.00	0.00	86.2	466
180	10	7.25	31.5	60	-	-	0.05	0.05	0.10	0.10	0.10	88.5	557
240	11	7.28	31.5	60	-	-	0.05	0.05	0.10	0.10	0.10	87.4	628
300	10	7.21	31.5	60	-	-	0.05	0.05	0.10	0.10	0.10	88.5	675
360	10	7.25	31.5	60	-	-	0.05	0.05	0.10	0.10	0.10	88.5	678

Time (min)	Porosity of media (f) Top layer	Medium layer	Bottom layer	$10^{-6}*\nu$ (m^2/s)	θ_1 (s)	θ_{2-5} (s)	G_1 (s^{-1})	G_2 (s^{-1})	G_3 (s^{-1})	G_4 (s^{-1})	G_5 (s^{-1})	G_{AVE} (s^{-1})
0	0.400	-	-	0.8127	100.7	215.8	12.2	8.4	11.8	0.0	0.0	6.5
30	0.400	-	-	0.7955	100.7	215.8	12.4	8.5	12.0	0.0	0.0	6.6
60	0.400	-	-	0.7870	100.7	215.8	12.4	8.5	12.0	0.0	0.0	6.6
90	0.400	-	-	0.7870	100.7	215.8	12.4	8.5	12.0	0.0	0.0	6.6
120	0.400	-	-	0.7870	100.7	215.8	17.6	12.0	12.0	0.0	0.0	8.3
150	0.400	-	-	0.7838	100.7	215.8	17.6	12.0	12.0	0.0	0.0	8.3
180	0.400	-	-	0.7789	100.7	215.8	12.5	8.5	12.1	12.1	12.1	11.5
240	0.400	-	-	0.7789	100.7	215.8	12.5	8.5	12.1	12.1	12.1	11.5
300	0.400	-	-	0.7789	100.7	215.8	12.5	8.5	12.1	12.1	12.1	11.5
360	0.400	-	-	0.7789	100.7	215.8	12.5	8.5	12.1	12.1	12.1	11.5

Conditions: Hydraulic rate = 2.5 m^3/m^2-h, Dose of PACl = 2.5 mg/L

: Media size = 10 mm, Media depth = 60 cm

Appendix Table D20 Experimental data of run no.20

Time (min)	Tb (NTU)	pH	Temp (^0C)	Bed Expansion (cm) 1	2	3	Δh_1 (m)	Δh_2 (m)	Δh_3 (m)	Δh_4 (m)	Δh_5 (m)	% Tb removal	Max Floc (µm)
0	85	6.95	31.8	15	15	-	0.05	0.00	0.05	-	-	-	-
30	45	7.16	32.0	15	15	-	0.10	0.05	0.05	-	-	47.1	94
60	27	7.18	31.8	15	15	-	0.10	0.05	0.05	-	-	70.7	212
90	14	7.15	31.8	15	15	-	0.10	0.10	0.05	-	-	84.8	423
120	16	7.19	31.8	15	15	-	0.10	0.10	0.05	-	-	82.6	556
150	15	7.14	32.0	15	15	-	0.10	0.10	0.05	-	-	83.7	667
180	13	7.07	32.0	15	15	-	0.10	0.10	0.05	-	-	85.9	829
240	15	7.06	32.0	15	15	-	0.10	0.10	0.05	-	-	83.7	912
300	13	7.11	32.0	15	15	-	0.10	0.10	0.05	-	-	85.9	1081
360	14	7.13	32.0	15	15	-	0.10	0.10	0.05	-	-	84.8	1109

Time (min)	Porosity of media (f) Top layer	Medium layer	Bottom layer	$10^{-6}*\nu$ (m^2/s)	θ_1 (s)	θ_{2-5} (s)	G_1 (S^{-1})	G_2 (S^{-1})	G_3 (S^{-1})	G_4 (S^{-1})	G_5 (S^{-1})	G_{AVE} (S^{-1})
0	0.360	0.400	-	0.7740	100.7	215.8	13.2	0.0	8.6	-	-	7.3
30	0.360	0.400	-	0.7708	100.7	215.8	18.7	8.8	8.6	-	-	12.0
60	0.360	0.400	-	0.7740	100.7	215.8	18.7	8.8	8.6	-	-	12.0
90	0.360	0.400	-	0.7740	100.7	215.8	18.7	12.4	8.6	-	-	13.2
120	0.360	0.400	-	0.7740	100.7	215.8	18.7	12.4	8.6	-	-	13.2
150	0.360	0.400	-	0.7708	100.7	215.8	18.7	12.5	8.6	-	-	13.3
180	0.360	0.400	-	0.7708	100.7	215.8	18.7	12.5	8.6	-	-	13.3
240	0.360	0.400	-	0.7708	100.7	215.8	18.7	12.5	8.6	-	-	13.3
300	0.360	0.400	-	0.7708	100.7	215.8	18.7	12.5	8.6	-	-	13.3
360	0.360	0.400	-	0.7708	100.7	215.8	18.7	12.5	8.6	-	-	13.3

Conditions: Hydraulic rate = 2.5 m^3/m^2-h, Dose of PACl = 2.5 mg/L.

: Media size = 6 mm, Media depth = 15 cm at top layer.

: Media size = 10 mm, Media depth = 15 cm at bottom layer

Appendix Table D21 Experimental data of run no.21

Time (min)	Tb (NTU)	pH	Temp (^0C)	Bed Expansion (cm) 1	2	3	Δh_1 (m)	Δh_2 (m)	Δh_3 (m)	Δh_4 (m)	Δh_5 (m)	% Tb removal	Max Floc (µm)
0	87	7.44	28.8	30	30	-	0.05	0.05	0.05	0.05	0.05	-	-
30	16	7.33	30.0	30	30	-	0.10	0.10	0.05	0.05	0.05	81.6	89
60	14	7.42	30.8	30	30	-	0.10	0.10	0.05	0.05	0.05	83.9	121
90	13	7.95	31.3	30	30	-	0.10	0.10	0.10	0.05	0.05	85.1	252
120	14	7.24	31.3	30	30	-	0.10	0.10	0.10	0.10	0.10	83.9	324
150	11	7.13	31.7	30	30	-	0.10	0.10	0.10	0.10	0.10	87.4	475
180	9	7.03	31.7	30	30	-	0.10	0.10	0.10	0.10	0.10	89.7	567
240	9	7.26	31.7	30	30	-	0.10	0.10	0.10	0.10	0.10	89.7	682
300	8	7.20	31.7	30	30	-	0.10	0.10	0.10	0.10	0.10	90.8	705
360	8	7.23	31.7	30	30	-	0.10	0.10	0.10	0.10	0.10	90.8	728

Time (min)	Porosity of media (f) Top layer	Medium layer	Bottom layer	$10^{-6}*\nu$ (m^2/s)	θ_1 (s)	θ_{2-5} (s)	G_1 (s^{-1})	G_2 (s^{-1})	G_3 (s^{-1})	G_4 (s^{-1})	G_5 (s^{-1})	G_{AVE} (s^{-1})
0	0.360	0.400	-	0.8250	100.7	215.8	12.8	8.7	8.5	8.3	8.3	9.3
30	0.360	0.400	-	0.8039	100.7	215.8	18.3	12.5	8.6	8.4	8.4	11.3
60	0.360	0.400	-	0.7904	100.7	215.8	18.5	12.6	8.7	8.5	8.5	11.4
90	0.360	0.400	-	0.7821	100.7	215.8	18.6	12.7	12.4	8.5	8.5	12.1
120	0.360	0.400	-	0.7821	100.7	215.8	18.6	12.7	12.4	12.1	12.1	13.6
150	0.360	0.400	-	0.7757	100.7	215.8	18.7	12.8	12.4	12.1	12.1	13.6
180	0.360	0.400	-	0.7757	100.7	215.8	18.7	12.8	12.4	12.1	12.1	13.6
240	0.360	0.400	-	0.7757	100.7	215.8	18.7	12.8	12.4	12.1	12.1	13.6
300	0.360	0.400	-	0.7757	100.7	215.8	18.7	12.8	12.4	12.1	12.1	13.6
360	0.360	0.400	-	0.7757	100.7	215.8	18.7	12.8	12.4	12.1	12.1	13.6

Conditions: Hydraulic rate = 2.5 m^3/m^2-h, Dose of PACl = 2.5 mg/L.

: Media size = 6 mm, Media depth = 30 cm at top layer.

: Media size = 10 mm, Media depth = 30 cm at bottom layer

Appendix Table D22 Experimental data of run no.22

Time (min)	Tb (NTU)	pH	Temp (^{0}C)	Bed Expansion (cm.) 1	2	3	Δh_1 (m)	Δh_2 (m)	Δh_3 (m)	Δh_4 (m)	Δh_5 (m)	% Tb removal	Max .Floc (µm)
0	84	7.42	30.7	15	15	-	0.10	0.10	0.10	-	-	-	-
30	17	7.39	30.8	15	15	-	0.10	0.10	0.10	-	-	79.8	104
60	13	7.43	31.2	15	15	-	0.10	0.10	0.10	-	-	84.5	236
90	12	7.46	31.8	15	15	-	0.10	0.10	0.10	-	-	85.7	306
120	13	7.35	31.6	15	15	-	0.10	0.10	0.10	-	-	84.5	434
150	12	7.31	31.6	15	15	-	0.10	0.10	0.20	-	-	85.7	529
180	11	7.34	31.2	15	15	-	0.10	0.10	0.20	-	-	86.9	634
240	9	7.27	31.2	15	15	-	0.10	0.10	0.20	-	-	89.3	765
300	9	7.80	31.2	15	15	-	0.10	0.10	0.20	-	-	89.3	774
360	9	7.30	31.2	15	15	-	0.10	0.10	0.20	-	-	89.3	827

Time (min)	Porosity of media (f) Top layer	Medium layer	Bottom layer	$10^{-6}*\nu$ (m^2/s)	θ_1 (s)	θ_{2-5} (s)	G_1 (S^{-1})	G_2 (S^{-1})	G_3 (S^{-1})	G_4 (S^{-1})	G_5 (S^{-1})	G_{AVE} (S^{-1})
0	0.340	0.360	-	0.7920	100.7	215.8	19.0	12.8	12.6	-	-	14.8
30	0.340	0.360	-	0.7900	100.7	215.8	19.0	12.8	12.6	-	-	14.8
60	0.340	0.360	-	0.7838	100.7	215.8	19.1	12.9	12.7	-	-	14.9
90	0.340	0.360	-	0.7740	100.7	215.8	19.2	13.0	12.8	-	-	15.0
120	0.340	0.360	-	0.7773	100.7	215.8	19.1	12.9	12.7	-	-	14.9
150	0.340	0.360	-	0.7773	100.7	215.8	19.2	12.9	18.0	-	-	16.7
180	0.340	0.360	-	0.7838	100.7	215.8	19.1	12.9	17.9	-	-	16.6
240	0.340	0.360	-	0.7838	100.7	215.8	19.1	12.9	17.9	-	-	16.6
300	0.340	0.360	-	0.7838	100.7	215.8	19.1	12.9	17.9	-	-	16.6
360	0.340	0.360	-	0.7838	100.7	215.8	19.1	12.9	17.9	-	-	16.6

Conditions: Hydraulic rate = 2.5 m^3/m^2-h, Dose of PACl = 2.5 mg/L.

: Media size = 3 mm, Media depth = 15 cm at top layer.

: Media size = 6 mm, Media depth = 15 cm at bottom layer

Appendix Table D23 Experimental data of run no.23

Time (min)	Tb (NTU)	pH	Temp (^0C)	Bed Expansion (cm) 1	2	3	Δh_1 (m)	Δh_2 (m)	Δh_3 (m)	Δh_4 (m)	Δh_5 (m)	% Tb removal	Max Floc (µm)
0	85	7.28	29.4	30	30	-	0.10	0.10	0.10	0.10	0.10	-	-
30	14	7.38	30.5	30	30	-	0.10	0.20	0.10	0.10	0.10	84.1	57
60	8	7.18	30.7	30	30	-	0.10	0.20	0.10	0.10	0.10	90.9	107
90	6	7.17	30.8	30	30	-	0.10	0.20	0.10	0.10	0.10	93.2	151
120	7	7.15	31.1	30	30	-	0.10	0.20	0.20	0.20	0.10	92.0	214
150	5	7.14	31.3	30	30	-	0.10	0.20	0.20	0.20	0.10	94.3	302
180	6	7.21	31.3	30	30	-	0.10	0.20	0.20	0.20	0.10	93.2	346
240	5	7.21	31.3	30	30	-	0.10	0.20	0.20	0.20	0.10	94.3	352
300	6	7.19	31.3	30	30	-	0.10	0.20	0.20	0.20	0.10	93.2	390
360	5	7.19	31.3	30	30	-	0.10	0.20	0.20	0.20	0.10	94.3	452

Time (min)	Porosity of media (f) Top layer	Medium layer	Bottom layer	$10^{-6}*\nu$ (m^2/s)	θ_1 (s)	θ_{2-5} (s)	G_1 (s^{-1})	G_2 (s^{-1})	G_3 (s^{-1})	G_4 (s^{-1})	G_5 (s^{-1})	G_{AVE} (s^{-1})
0	0.340	0.360	-	0.8144	100.7	215.8	18.8	12.8	12.6	12.5	12.5	13.8
30	0.340	0.360	-	0.7955	100.7	215.8	19.0	18.3	12.8	12.6	12.6	15.1
60	0.340	0.360	-	0.7920	100.7	215.8	19.0	18.4	12.8	12.6	12.6	15.1
90	0.340	0.360	-	0.7900	100.7	215.8	19.0	18.4	12.8	12.6	12.6	15.1
120	0.340	0.360	-	0.7854	100.7	215.8	19.1	18.5	18.2	17.9	12.7	17.3
150	0.340	0.360	-	0.7821	100.7	215.8	19.1	18.5	18.2	18.0	12.7	17.3
180	0.340	0.360	-	0.7821	100.7	215.8	19.1	18.5	18.2	18.0	12.7	17.3
240	0.340	0.360	-	0.7821	100.7	215.8	19.1	18.5	18.2	18.0	12.7	17.3
300	0.340	0.360	-	0.7821	100.7	215.8	19.1	18.5	18.2	18.0	12.7	17.3
360	0.340	0.360	-	0.7821	100.7	215.8	19.1	18.5	18.2	18.0	12.7	17.3

Conditions: Hydraulic rate = 2.5 m^3/m^2-h, Dose of PACl = 2.5 mg/L

: Media size = 3 mm, Media depth = 30 cm at top layer.

: Media size = 6 mm, Media depth = 30 cm at bottom layer

Appendix Table D24 Experimental data of run no.24

Time (min)	Tb (NTU)	pH	Temp (^{0}C)	Bed Expansion (cm) 1	2	3	Δh_1 (m)	Δh_2 (m)	Δh_3 (m)	Δh_4 (m)	Δh_5 (m)	% Tb removal	Max Floc (µm)
0	85	7.73	27.6	15	15	-	0.05	0.05	0.05	0.05	-	-	-
30	51	7.35	28.2	15	15	-	0.10	0.20	0.10	0.10	-	40.0	44
60	13	7.3	28.6	15	15	-	0.10	0.10	0.10	0.10	-	84.7	112
90	11	7.23	28.7	15	15	-	0.20	0.10	0.10	0.10	-	87.1	133
120	12	7.13	29.1	15	15	-	0.20	0.10	0.10	0.10	-	85.9	299
150	11	7.21	29.1	15	15	-	0.20	0.20	0.10	0.10	-	87.1	307
180	11	7.17	29.5	15	15	-	0.20	0.20	0.10	0.10	-	87.1	389
240	11	7.39	29.5	15	15	-	0.20	0.20	0.10	0.10	-	87.1	451
300	11	7.22	29.5	15	15	-	0.20	0.20	0.10	0.10	-	87.1	465
360	11	7.13	29.5	15	15	-	0.20	0.20	0.10	0.10	-	87.1	526

Time (min)	Porosity of media (f) Top layer	Medium layer	Bottom layer	$10^{-6}*\nu$ (m^2/s)	θ_1 (s)	θ_{2-5} (s)	G_1 (S^{-1})	G_2 (S^{-1})	G_3 (S^{-1})	G_4 (S^{-1})	G_5 (S^{-1})	G_{AVE} (S^{-1})
0	0.340	0.400	-	0.8469	100.7	215.8	13.0	8.5	8.2	8.2	-	9.5
30	0.340	0.400	-	0.8358	100.7	215.8	18.5	17.1	11.7	11.7	-	14.7
60	0.340	0.400	-	0.8286	100.7	215.8	18.6	12.2	11.7	11.7	-	13.5
90	0.340	0.400	-	0.8268	100.7	215.8	26.3	12.2	11.7	11.7	-	15.5
120	0.340	0.400	-	0.8197	100.7	215.8	26.4	12.2	11.8	11.8	-	15.6
150	0.340	0.400	-	0.8197	100.7	215.8	26.4	17.3	11.8	11.8	-	16.8
180	0.340	0.400	-	0.8127	100.7	215.8	26.6	17.4	11.8	11.8	-	16.9
240	0.340	0.400	-	0.8127	100.7	215.8	26.6	17.4	11.8	11.8	-	16.9
300	0.340	0.400	-	0.8127	100.7	215.8	26.6	17.4	11.8	11.8	-	16.9
360	0.340	0.400	-	0.8127	100.7	215.8	26.6	17.4	11.8	11.8	-	16.9

Conditions: Hydraulic rate = 2.5 m^3/m^2-h, Dose of PACl = 2.5 mg/L

: Media size = 3 mm, Media depth = 15 cm at top layer.

: Media size = 10 mm, Media depth = 15 cm at bottom layer

Appendix Table D25 Experimental data of run no.25

Time (min)	Tb (NTU)	pH	Temp (^{0}C)	Bed Expansion (cm) 1	2	3	Δh_1 (m)	Δh_2 (m)	Δh_3 (m)	Δh_4 (m)	Δh_5 (m)	% Tb removal	Max Floc (µm)
0	82	6.86	28.7	30	30	-	0.10	0.20	0.10	0.10	0.05	-	-
30	16	7.20	29.7	30	30	-	0.10	0.20	0.10	0.10	0.10	80.5	41
60	15	7.15	29.8	30	30	-	0.10	0.30	0.10	0.10	0.10	81.7	103
90	8	7.29	29.9	30	30	-	0.10	0.20	0.10	0.10	0.10	90.2	108
120	7	7.30	30.0	30	30	-	0.10	0.20	0.10	0.10	0.10	91.5	123
150	7	7.43	29.9	30	30	-	0.20	0.40	0.10	0.10	0.10	91.5	169
180	6	7.67	29.9	30	30	-	0.20	0.40	0.10	0.10	0.10	92.7	185
240	6	7.59	29.9	30	30	-	0.20	0.40	0.10	0.10	0.10	92.7	217
300	6	7.50	29.9	30	30	-	0.20	0.40	0.10	0.10	0.10	92.7	256
360	6	7.44	29.9	30	30	-	0.20	0.40	0.10	0.10	0.10	92.7	296

Time (min)	Porosity of media (f) Top layer	Medium layer	Bottom layer	$10^{-6}*\nu$ (m^2/s)	θ_1 (s)	θ_{2-5} (s)	G_1 (s^{-1})	G_2 (s^{-1})	G_3 (s^{-1})	G_4 (s^{-1})	G_5 (s^{-1})	G_{AVE} (s^{-1})
0	0.340	0.400	-	0.8268	100.7	215.8	18.6	18.0	12.2	11.7	8.3	13.8
30	0.340	0.400	-	0.8092	100.7	215.8	18.8	18.2	12.3	11.9	11.9	14.6
60	0.340	0.400	-	0.8074	100.7	215.8	18.8	22.3	12.3	11.9	11.9	15.4
90	0.340	0.400	-	0.8057	100.7	215.8	18.9	18.2	12.3	11.9	11.9	14.6
120	0.340	0.400	-	0.8039	100.7	215.8	18.9	18.2	12.4	11.9	11.9	14.7
150	0.340	0.400	-	0.8057	100.7	215.8	26.7	25.8	12.3	11.9	11.9	17.7
180	0.340	0.400	-	0.8057	100.7	215.8	26.7	25.8	12.3	11.9	11.9	17.7
240	0.340	0.400	-	0.8057	100.7	215.8	26.7	25.8	12.3	11.9	11.9	17.7
300	0.340	0.400	-	0.8057	100.7	215.8	26.7	25.8	12.3	11.9	11.9	17.7
360	0.340	0.400	-	0.8057	100.7	215.8	26.7	25.8	12.3	11.9	11.9	17.7

Conditions: Hydraulic rate = 2.5 m^3/m^2-h, Dose of PACl = 2.5 mg/L

: Media size = 3 mm, Media depth = 30 cm at top layer.

: Media size = 10 mm, Media depth = 30 cm at bottom layer

Appendix Table D26 Experimental data of run no.26

Time (min)	Tb (NTU)	pH	Temp (^{0}C)	Bed Expansion (cm) 1	2	3	Δh_1 (m)	Δh_2 (m)	Δh_3 (m)	Δh_4 (m)	Δh_5 (m)	% Tb removal	Max Floc (μm)
0	86	7.41	28.7	10	10	10	0.10	0.10	0.10	-	-	-	-
30	18	7.17	29.4	10	10	10	0.10	0.10	0.10	-	-	79.1	91
60	17	7.27	29.7	10	10	10	0.10	0.20	0.10	-	-	80.2	138
90	18	7.31	29.8	10	10	10	0.10	0.20	0.10	-	-	79.1	288
120	15	7.23	29.9	10	10	10	0.10	0.20	0.10	-	-	82.6	378
150	13	7.23	29.9	10	10	10	0.10	0.20	0.10	-	-	84.9	478
180	13	7.23	29.9	10	10	10	0.10	0.20	0.10	-	-	84.9	613
240	12	7.28	29.9	10	10	10	0.10	0.20	0.10	-	-	86.0	792
300	11	7.21	29.9	10	10	10	0.10	0.20	0.10	-	-	87.2	857
360	12	7.20	29.9	10	10	10	0.10	0.20	0.10	-	-	86.0	884

Time (min)	Porosity of media (f) Top layer	Medium layer	Bottom layer	$10^{-6}*\nu$ (m^2/s)	θ_1 (s)	θ_{2-5} (s)	G_1 (s^{-1})	G_2 (s^{-1})	G_3 (s^{-1})	G_4 (s^{-1})	G_5 (s^{-1})	G_{AVE} (s^{-1})
0	0.340	0.360	0.400	0.8268	100.7	215.8	18.6	11.5	11.7	-	-	14.0
30	0.340	0.360	0.400	0.8144	100.7	215.8	18.8	11.6	11.8	-	-	14.1
60	0.340	0.360	0.400	0.8092	100.7	215.8	18.8	16.5	11.9	-	-	15.7
90	0.340	0.360	0.400	0.8074	100.7	215.8	18.8	16.5	11.9	-	-	15.7
120	0.340	0.360	0.400	0.8057	100.7	215.8	18.9	16.5	11.9	-	-	15.8
150	0.340	0.360	0.400	0.8057	100.7	215.8	18.9	16.5	11.9	-	-	15.8
180	0.340	0.360	0.400	0.8057	100.7	215.8	18.9	16.5	11.9	-	-	15.8
240	0.340	0.360	0.400	0.8057	100.7	215.8	18.9	16.5	11.9	-	-	15.8
300	0.340	0.360	0.400	0.8057	100.7	215.8	18.9	16.5	11.9	-	-	15.8
360	0.340	0.360	0.400	0.8057	100.7	215.8	18.9	16.5	11.9	-	-	15.8

Conditions: Hydraulic rate = 2.5 m^3/m^2-h, Dose of PACl = 2.5 mg/L

: Media size = 3 mm, Media depth = 10 cm at top layer.

: Media size = 6 mm, Media depth = 10 cm at medium layer.

: Media size = 10 mm, Media depth = 10 cm at bottom layer

<u>Appendix Table D27</u> Experimental data of run no.27

Time (min)	Tb (NTU)	pH	Temp (^{0}C)	Bed Expansion (cm) 1	2	3	Δh_1 (m)	Δh_2 (m)	Δh_3 (m)	Δh_4 (m)	Δh_5 (m)	% Tb removal	Max Floc (µm)
0	85	7.33	28.7	20	20	20	0.10	0.10	0.10	0.10	0.10	-	-
30	11	7.14	29.4	20	20	20	0.10	0.10	0.10	0.10	0.10	87.1	77
60	10	7.27	29.7	20	20	20	0.20	0.20	0.10	0.10	0.05	88.2	144
90	9	7.26	29.8	20	20	20	0.20	0.20	0.10	0.10	0.05	89.4	237
120	10	7.29	29.9	20	20	20	0.20	0.20	0.10	0.10	0.05	88.2	297
150	8	7.28	29.9	20	20	20	0.25	0.20	0.10	0.10	0.05	90.6	440
180	7	7.29	29.9	20	20	20	0.25	0.20	0.10	0.10	0.05	91.8	478
240	8	7.23	29.9	20	20	20	0.25	0.20	0.10	0.10	0.05	90.6	572
300	8	7.26	29.9	20	20	20	0.25	0.20	0.10	0.10	0.05	90.6	688
360	8	7.05	29.9	20	20	20	0.25	0.20	0.10	0.10	0.05	90.6	729

Time (min)	Porosity of media (f) Top layer	Medium layer	Bottom layer	$10^{-6}*\nu$ (m^2/s)	θ_1 (s)	θ_{2-5} (s)	G_1 (s^{-1})	G_2 (s^{-1})	G_3 (s^{-1})	G_4 (s^{-1})	G_5 (s^{-1})	G_{AVE} (s^{-1})
0	0.340	0.360	0.400	0.8322	100.7	215.8	18.6	12.5	12.3	10.7	11.7	13.2
30	0.340	0.360	0.400	0.8057	100.7	215.8	18.9	12.7	12.5	10.9	11.9	13.4
60	0.340	0.360	0.400	0.7990	100.7	215.8	26.8	18.0	12.6	10.9	8.4	15.3
90	0.340	0.360	0.400	0.7990	100.7	215.8	26.8	18.0	12.6	10.9	8.4	15.3
120	0.340	0.360	0.400	0.7950	100.7	215.8	26.8	18.1	12.6	11.0	8.5	15.4
150	0.340	0.360	0.400	0.7950	100.7	215.8	30.0	18.1	12.6	11.0	8.5	16.0
180	0.340	0.360	0.400	0.7940	100.7	215.8	30.0	18.1	12.6	11.0	8.5	16.0
240	0.340	0.360	0.400	0.7940	100.7	215.8	30.0	18.1	12.6	11.0	8.5	16.0
300	0.340	0.360	0.400	0.7940	100.7	215.8	30.0	18.1	12.6	11.0	8.5	16.0
360	0.340	0.360	0.400	0.7940	100.7	215.8	30.0	18.1	12.6	11.0	8.5	16.0

Conditions: Hydraulic rate = 2.5 m^3/m^2-h, Dose of PACl = 2.5 mg/L

: Media size = 3 mm, Media depth = 20 cm at top layer.

: Media size = 6 mm, Media depth = 20 cm at medium layer.

: Media size = 10 mm, Media depth = 20 cm at bottom layer

APPENDIX E

(STEADY STATE MAXIMUM FLOC SIZE)

Appendix Table E1 Maximum floc size at steady state; d_S of run no.1

Time (minute)	Maximum floc experiment at time " t " (µm)	Maximum floc estimate at time " t " (µm)	K (minute)	d_S (µm)
30	40	70	660	1,601
60	117	133		
90	134	192		
120	209	246		
150	287	296		
180	367	343		
240	416	427		
300	490	500		
360	571	565		

Appendix Table E2 Maximum floc size at steady state; d_S of run no.2

Time (minute)	Maximum floc experiment at time " t " (µm)	Maximum floc estimate at time " t " (µm)	K (minute)	d_S (µm)
30	70	89	586	1,891
60	123	171		
90	265	247		
120	297	318		
150	361	384		
180	475	445		
240	559	555		
300	641	653		
360	749	740		

Appendix Table E3 Maximum floc size at steady state; d_S of run no.3

Time (minute)	Maximum floc experiment at time " t " (µm)	Maximum floc estimate at time " t " (µm)	K (minute)	d_S (µm)
30	45	64	822	1,947
60	112	126		
90	198	184		
120	216	240		
150	324	293		
180	348	344		
240	496	440		
300	535	528		
360	678	609		
420	686	684		
480	690	754		

Appendix Table E4 Maximum floc size at steady state; d_S of run no.4

Time (minute)	Maximum floc experiment at time " t " (µm)	Maximum floc estimate at time " t " (µm)	K (minute)	d_S (µm)
30	53	72	348	905
60	97	133		
90	136	186		
120	174	232		
150	275	272		
180	307	308		
240	363	369		
300	411	419		
360	476	460		

<u>Appendix Table E5</u> Maximum floc size at steady state; d_S of run no.5

Time (minute)	Maximum floc experiment at time " t " (µm)	Maximum floc estimate at time " t " (µm)	K (minute)	d_S (µm)
30	49	55	552	1,311
60	104	108		
90	141	159		
120	196	209		
150	277	257		
180	330	304		
240	394	394		
300	462	478		
360	516	558		

<u>Appendix Table E6</u> Maximum floc size at steady state; d_S of run no.6

Time (minute)	Maximum floc experiment at time " t " (µm)	Maximum floc estimate at time " t " (µm)	K (minute)	d_S (µm)
30	44	80	358	1,032
60	102	148		
90	156	208		
120	244	259		
150	311	305		
180	404	346		
240	413	415		
300	458	471		
360	477	518		

<u>Appendix Table E7</u> Maximum floc size at steady state; d_S of run no.7

Time (minute)	Maximum floc experiment at time " t " (µm)	Maximum floc estimate at time " t " (µm)	K (minute)	d_S (µm)
30	52	61	642	1,374
60	97	117		
90	144	169		
120	202	216		
150	263	260		
180	345	301		
240	384	374		
300	467	437		
360	486	494		
420	563	543		
480	539	588		
540	547	628		

Appendix Table E8 Maximum floc size at steady state; d_S of run no.8

Time (minute)	Maximum floc experiment at time " t " (μm)	Maximum floc estimate at time " t " (μm)	K (minute)	d_S (μm)
60	78	152	351	557
120	133	223		
180	236	264		
240	281	291		
300	307	310		
360	334	324		
420	344	335		
480	356	344		
540	354	351		
600	366	357		
660	362	362		
720	365	366		
780	368	369		
840	378	373		
900	372	375		
960	380	378		
1020	376	380		
1080	373	382		
1140	383	384		
1200	379	385		
1260	387	387		
1320	389	388		
1380	385	389		
1440	382	391		

Appendix Table E9 Maximum floc size at steady state; d_S of run no.9

Time (minute)	Maximum floc experiment at time " t " (µm)	Maximum floc estimate at time " t " (µm)	K (minute)	d_S (µm)
30	0	0	576	734
60	0	0		
90	62	99		
120	101	127		
150	143	152		
180	195	175		
240	214	216		
300	248	251		
360	275	282		

Appendix Table E10 Maximum floc size at steady state; d_S of run no.10

Time (minute)	Maximum floc experiment at time " t " (µm)	Maximum floc estimate at time " t " (µm)	K (minute)	d_S (µm)
30	45	36	600	807
60	59	69		
90	90	100		
120	109	130		
150	123	157		
180	142	183		
240	236	230		
300	252	272		
360	327	309		

Appendix Table E11 Maximum floc size at steady state; d_S of run no.11

Time (minute)	Maximum floc experiment at time " t " (μm)	Maximum floc estimate at time " t " (μm)	K (minute)	d_S (μm)
30	49	51	405	747
60	74	96		
90	107	136		
120	132	171		
150	193	202		
180	247	230		
240	271	278		
300	326	318		
360	373	351		
420	348	380		

Appendix Table E12 Maximum floc size at steady state; d_S of run no.12

Time (minute)	Maximum floc experiment at time " t " (μm)	Maximum floc estimate at time " t " (μm)	K (minute)	d_S (μm)
30	67	62	381	847
60	92	115		
90	132	162		
120	195	203		
150	233	240		
180	272	272		
240	357	328		
300	384	373		
360	406	412		
420	413	444		

Appendix Table E13 Maximum floc size at steady state; d_S of run no.13

Time (minute)	Maximum floc experiment at time " t " (μm)	Maximum floc estimate at time " t " (μm)	K (minute)	d_S (μm)
30	42	44	224	494
60	61	83		
90	75	117		
120	106	148		
150	128	176		
180	198	201		
240	255	245		
300	286	282		
360	303	314		

Appendix Table E14 Maximum floc size at steady state; d_S of run no.14

Time (minute)	Maximum floc experiment at time " t " (µm)	Maximum floc estimate at time " t " (µm)	K (minute)	d_S (µm)
30	98	105	110	1,114
60	146	205		
90	223	301		
120	362	392		
150	491	480		
180	690	563		
240	771	721		
300	809	815		
360	855	854		

Appendix Table E15 Maximum floc size at steady state; d_S of run no.15

Time (minute)	Maximum floc experiment at time " t " (µm)	Maximum floc estimate at time " t " (µm)	K (minute)	d_S (µm)
30	60	84	320	980
60	108	155		
90	126	215		
120	254	267		
150	335	312		
180	360	352		
240	434	420		
300	456	474		
360	498	518		

<u>Appendix Table E16</u> Maximum floc size at steady state; d_S of run no.16

Time (minute)	Maximum floc experiment at time " t " (µm)	Maximum floc estimate at time " t " (µm)	K (minute)	d_S (µm)
30	82	112	136	922
60	117	208		
90	175	291		
120	331	363		
150	484	427		
180	523	485		
240	590	582		
300	642	661		
360	692	727		

<u>Appendix Table E17</u> Maximum floc size at steady state; d_S of run no.17

Time (minute)	Maximum floc experiment at time " t " (µm)	Maximum floc estimate at time " t " (µm)	K (minute)	d_S (µm)
30	42	65	227	755
60	85	124		
90	134	177		
120	198	224		
150	253	267		
180	345	307		
240	354	376		
300	457	435		
360	466	486		

Appendix Table E18 Maximum floc size at steady state; d_S of run no.18

Time (minute)	Maximum floc experiment at time " t " (μm)	Maximum floc estimate at time " t " (μm)	K (minute)	d_S (μm)
30	83	218	234	1,913
60	218	391		
90	497	532		
120	635	649		
150	784	748		
180	987	833		
240	993	970		
300	1063	1076		
360	1081	1160		

Appendix Table E19 Maximum floc size at steady state; d_S of run no.19

Time (minute)	Maximum floc experiment at time " t " (μm)	Maximum floc estimate at time " t " (μm)	K (minute)	d_S (μm)
30	79	78	637	1,739
60	122	150		
90	219	246		
120	351	333		
150	466	420		
180	557	498		
240	628	609		
300	675	667		
360	678	712		

Appendix Table E20 Maximum floc size at steady state; d_S of run no.20

Time (minute)	Maximum floc experiment at time " t " (µm)	Maximum floc estimate at time " t " (µm)	K (minute)	d_S (µm)
30	94	185	206	1,757
60	212	341		
90	423	474		
120	556	590		
150	667	691		
180	829	780		
240	912	929		
300	1081	1050		
360	1109	1150		

Appendix Table E21 Maximum floc size at steady state; d_S of run no.21

Time (minute)	Maximum floc experiment at time " t " (µm)	Maximum floc estimate at time " t " (µm)	K (minute)	d_S (µm)
30	89	143	238	1,274
60	121	257		
90	252	350		
120	324	427		
150	475	493		
180	567	549		
240	682	640		
300	705	710		
360	728	767		

Appendix Table E22 Maximum floc size at steady state; d_S of run no.22

Time (minute)	Maximum floc experiment at time " t " (μm)	Maximum floc estimate at time " t " (μm)	K (minute)	d_S (μm)
30	104	139	151	1,186
60	236	258		
90	306	360		
120	434	449		
150	529	527		
180	634	596		
240	765	712		
300	774	789		
360	827	836		

Appendix Table E23 Maximum floc size at steady state; d_S of run no.23

Time (minute)	Maximum floc experiment at time " t " (μm)	Maximum floc estimate at time " t " (μm)	K (minute)	d_S (μm)
30	57	72	340	891
60	107	134		
90	151	187		
120	214	233		
150	302	273		
180	346	309		
240	352	369		
300	390	418		
360	452	458		

Appendix Table E24 Maximum floc size at steady state; d_S of run no.24

Time (minute)	Maximum floc experiment at time " t " (µm)	Maximum floc estimate at time " t " (µm)	K (minute)	d_S (µm)
30	44	86	319	1,007
60	112	159		
90	133	221		
120	299	275		
150	307	322		
180	389	363		
240	451	432		
300	465	488		
360	526	534		

Appendix Table E25 Maximum floc size at steady state; d_S of run no.25

Time (minute)	Maximum floc experiment at time " t " (µm)	Maximum floc estimate at time " t " (µm)	K (minute)	d_S (µm)
30	41	36	676	856
60	103	70		
90	108	101		
120	123	129		
150	169	156		
180	185	180		
240	217	224		
300	256	263		
360	296	298		

Appendix Table E26 Maximum floc size at steady state; d_S of run no.26

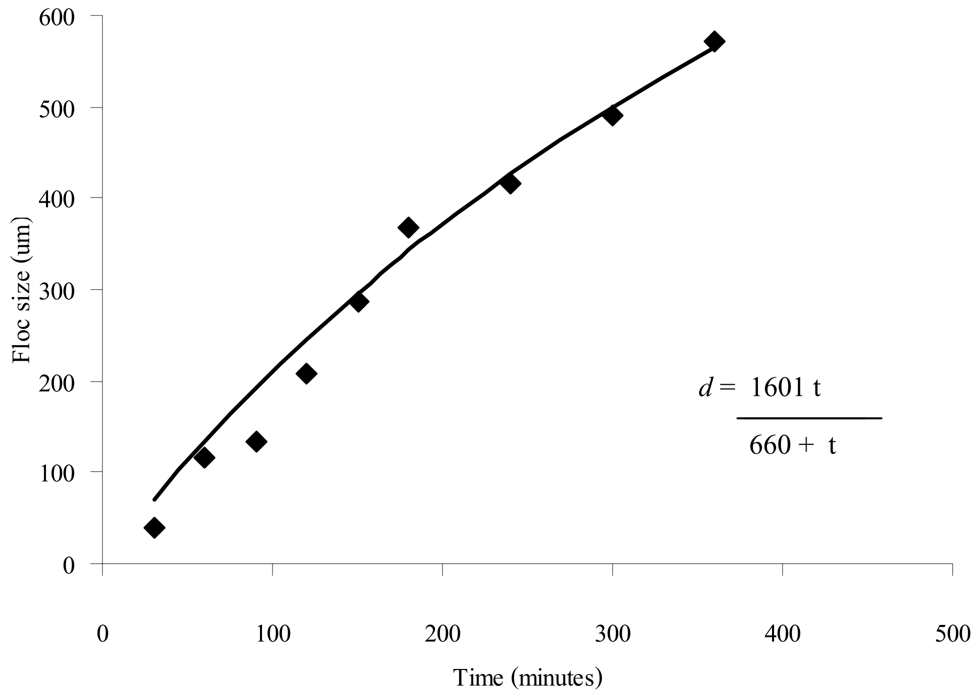
Time (minute)	Maximum floc experiment at time " t " (μm)	Maximum floc estimate at time " t " (μm)	K (minute)	d_S (μm)
30	91	100	321	1,750
60	138	198		
90	288	292		
120	378	384		
150	478	473		
180	613	560		
240	792	726		
300	857	845		
360	884	925		

Appendix Table E27 Maximum floc size at steady state; d_S of run no.27

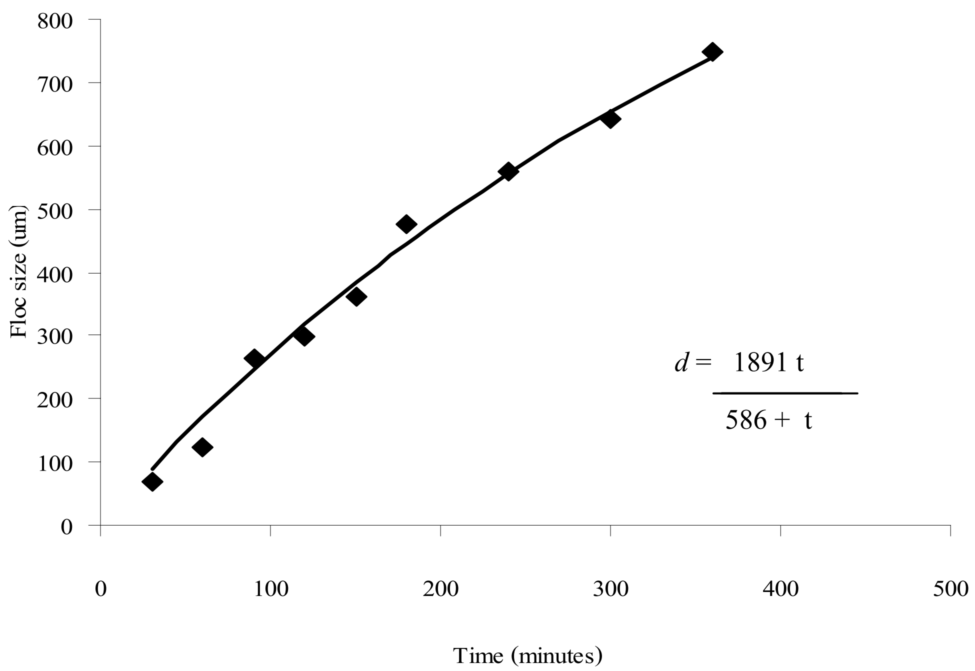
Time (minute)	Maximum floc experiment at time " t " (μm)	Maximum floc estimate at time " t " (μm)	K (minute)	d_S (μm)
30	77	105	447	1,662
60	144	197		
90	237	279		
120	297	352		
150	440	418		
180	478	477		
240	572	581		
300	688	667		
360	729	741		

APPENDIX FIGURE E

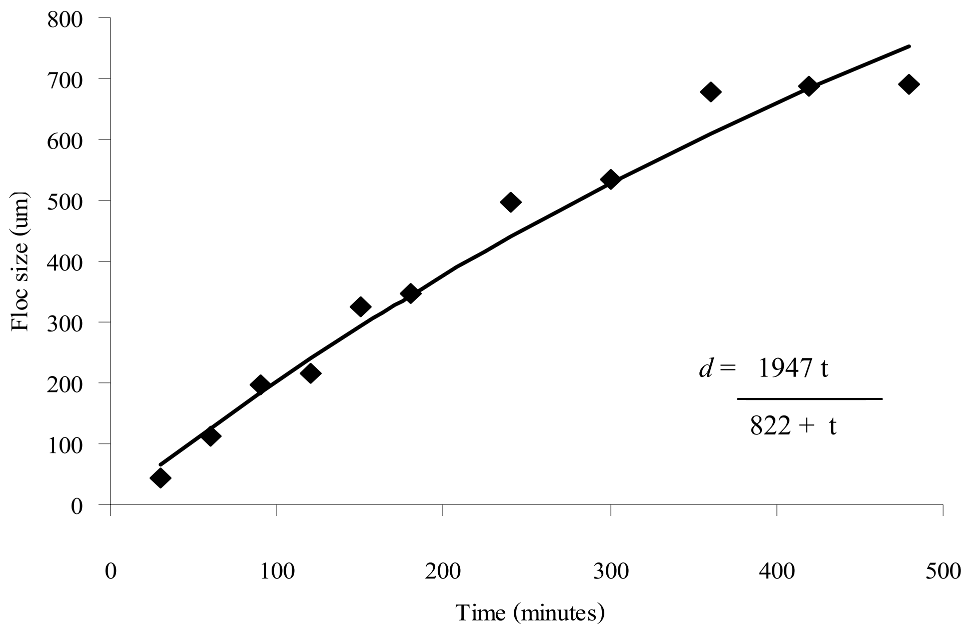
(STEADY STATE MAXIMUM FLOC SIZE)



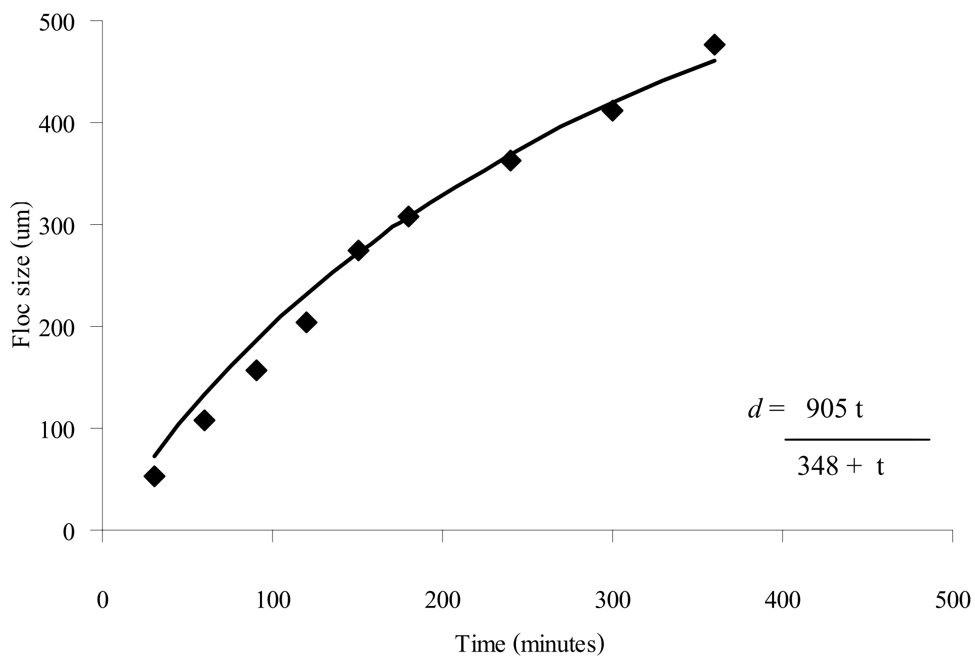
Appendix Figure E1 Maximum floc size at steady state (μm); d_s of run no.1



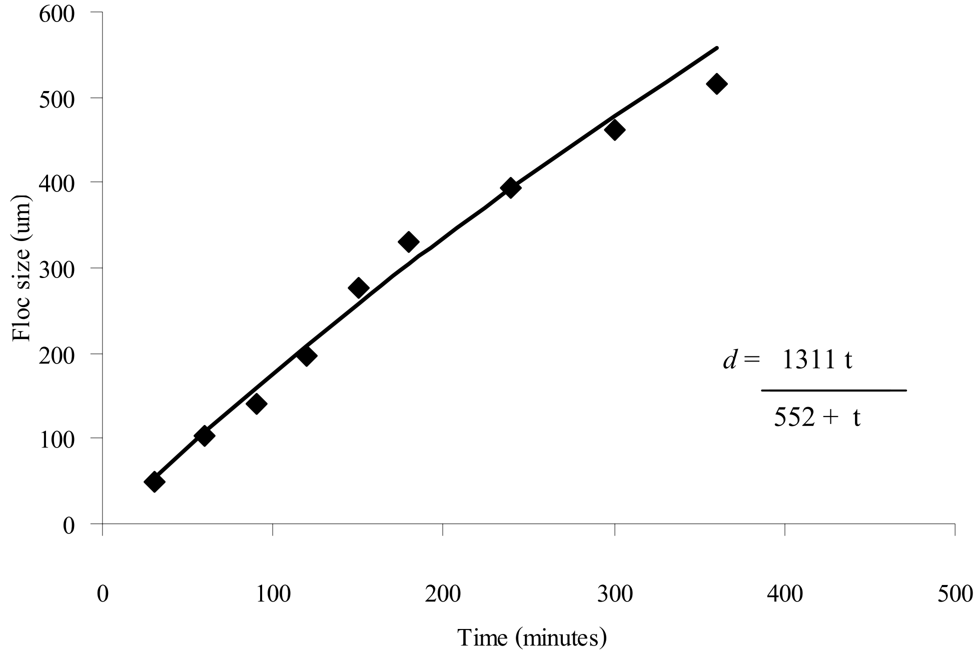
Appendix Figure E2 Maximum floc size at steady state (μm); d_s of run no.2



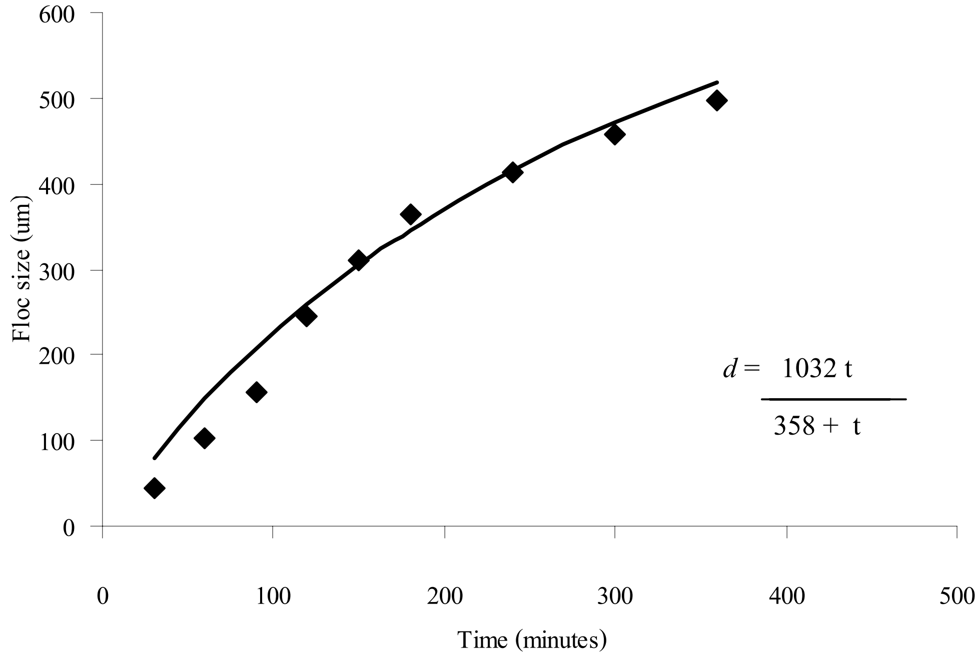
Appendix Figure E3 Maximum floc size at steady state (µm); d_S of run no.3



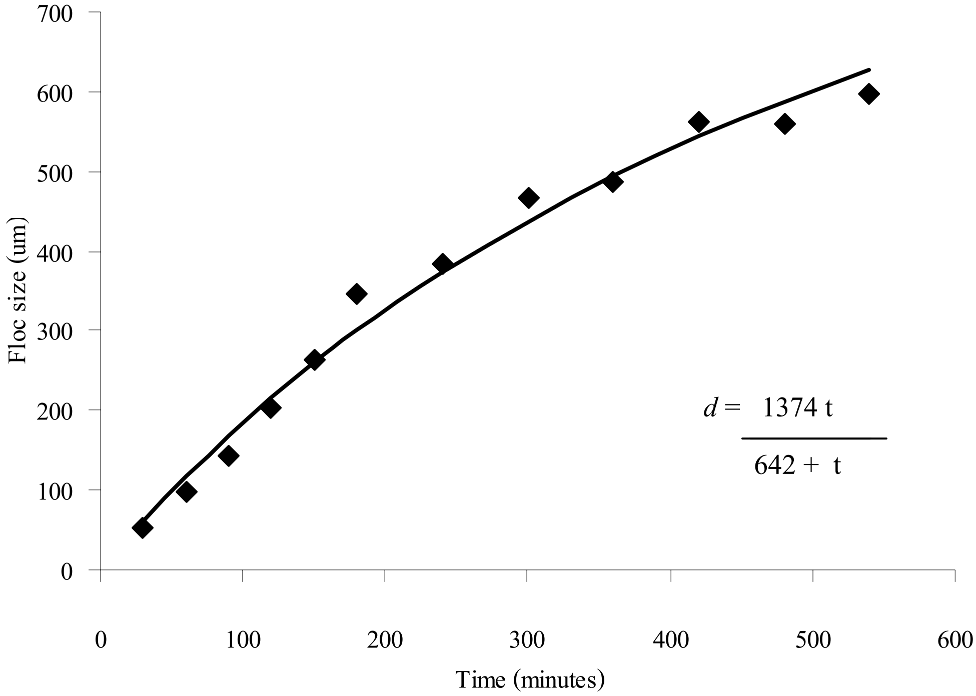
Appendix Figure E4 Maximum floc size at steady state (µm); d_S of run no.4



Appendix Figure E5 Maximum floc size at steady state (μm); d_S of run no.5



Appendix Figure E6 Maximum floc size at steady state (μm); d_S of run no.6



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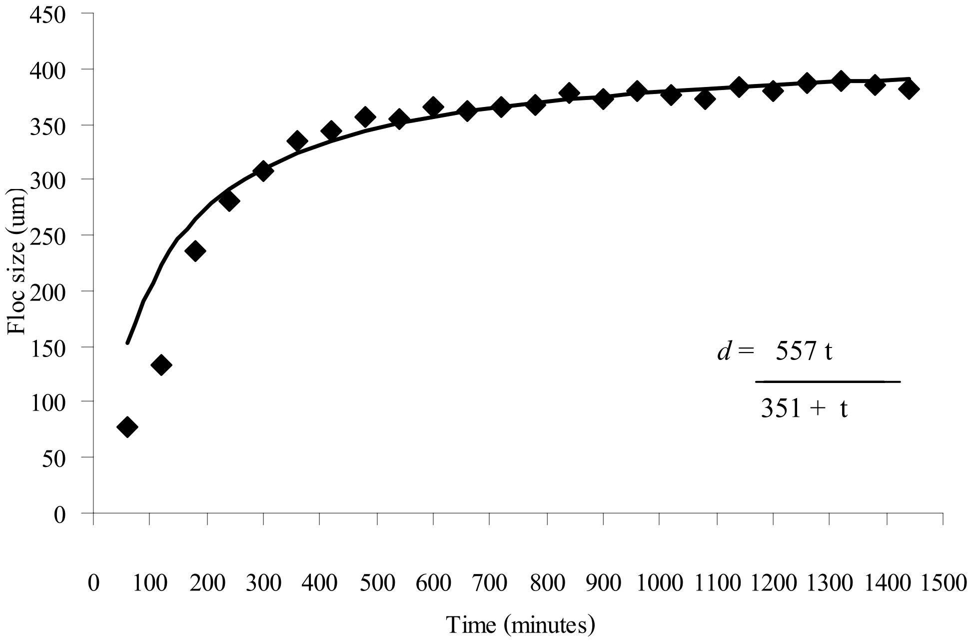
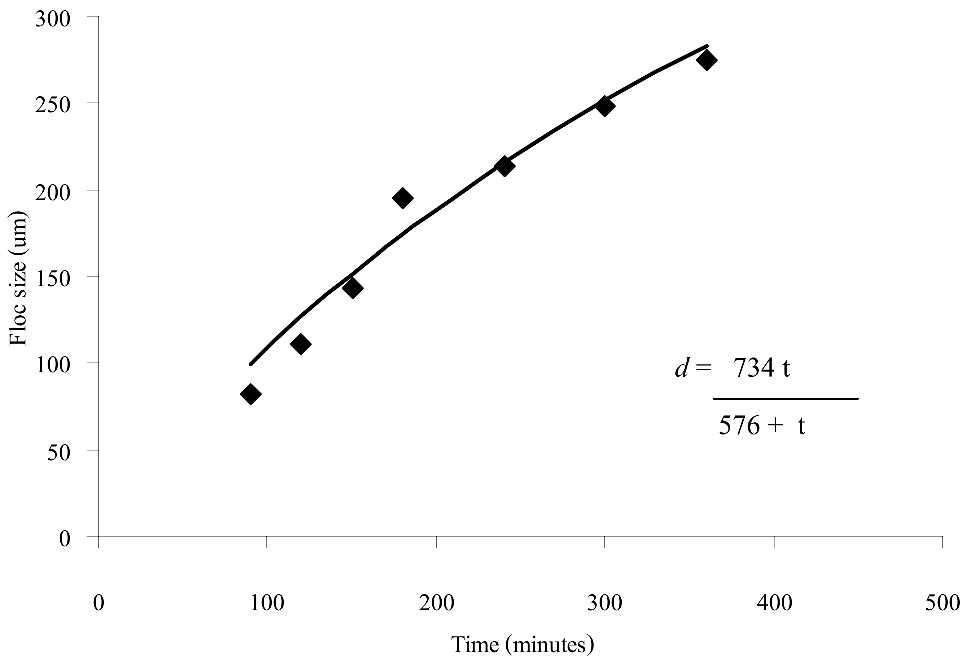
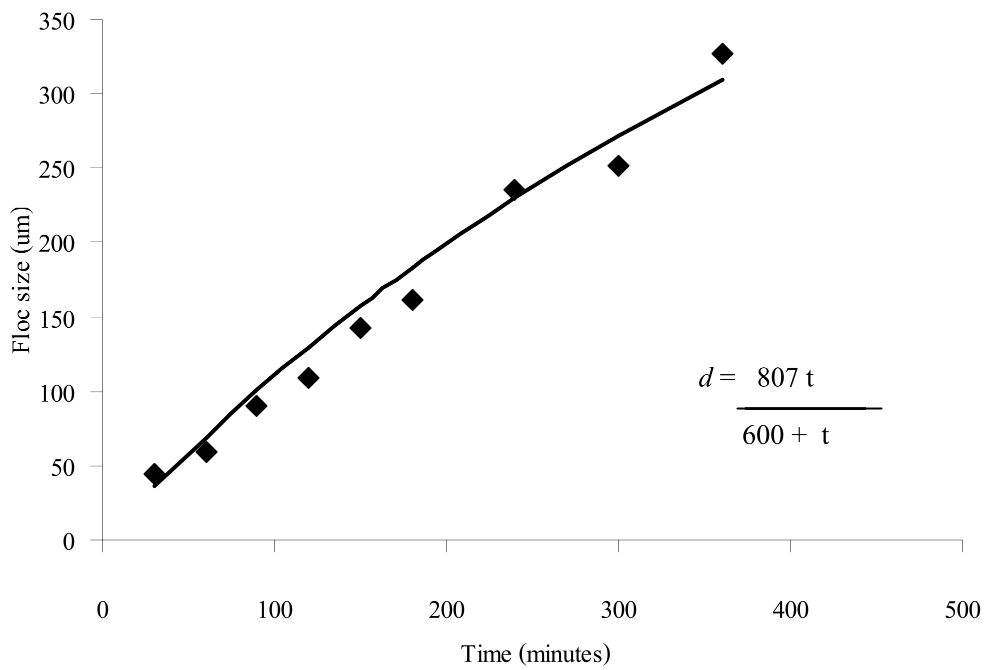
Appendix Figure E7 Maximum floc size at steady state (µm); d_S of run no.7



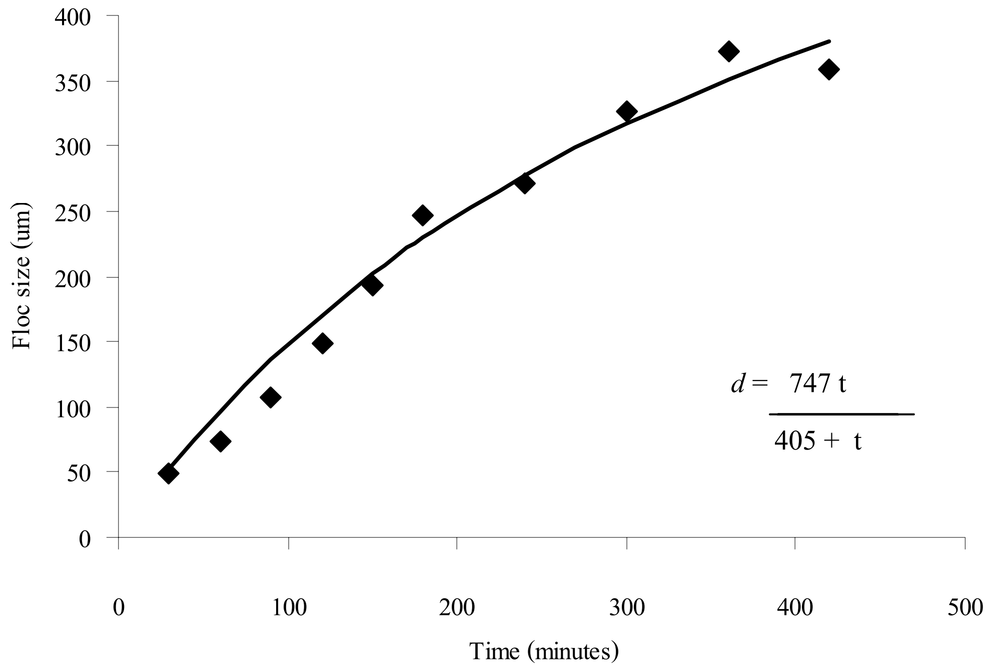
Appendix Figure E8 Maximum floc size at steady state (µm); d_S of run no.8



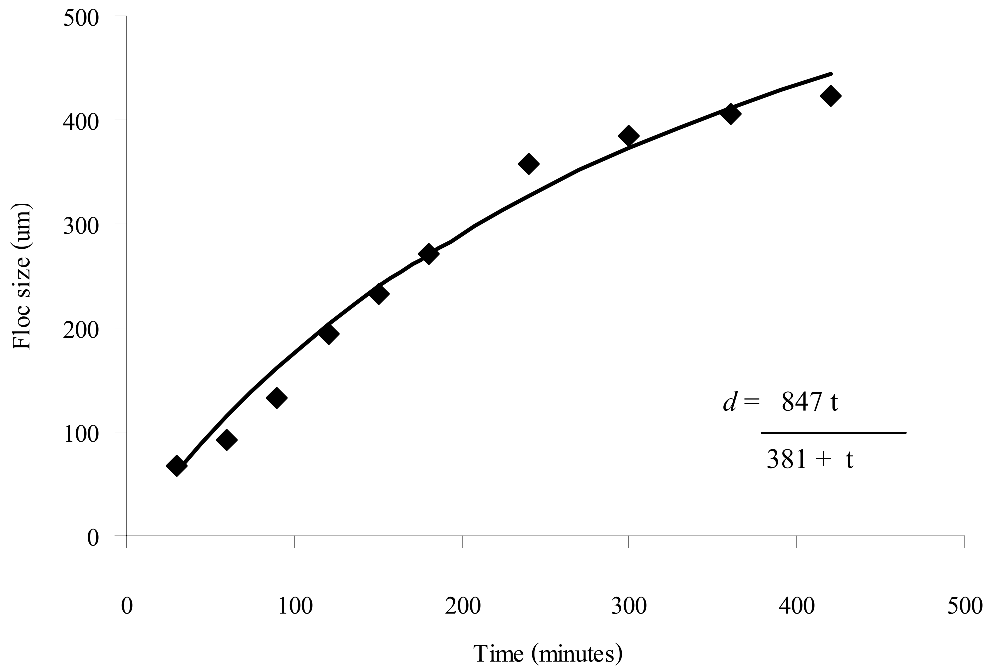
Appendix Figure E9 Maximum floc size at steady state (μm); d_S of run no.9



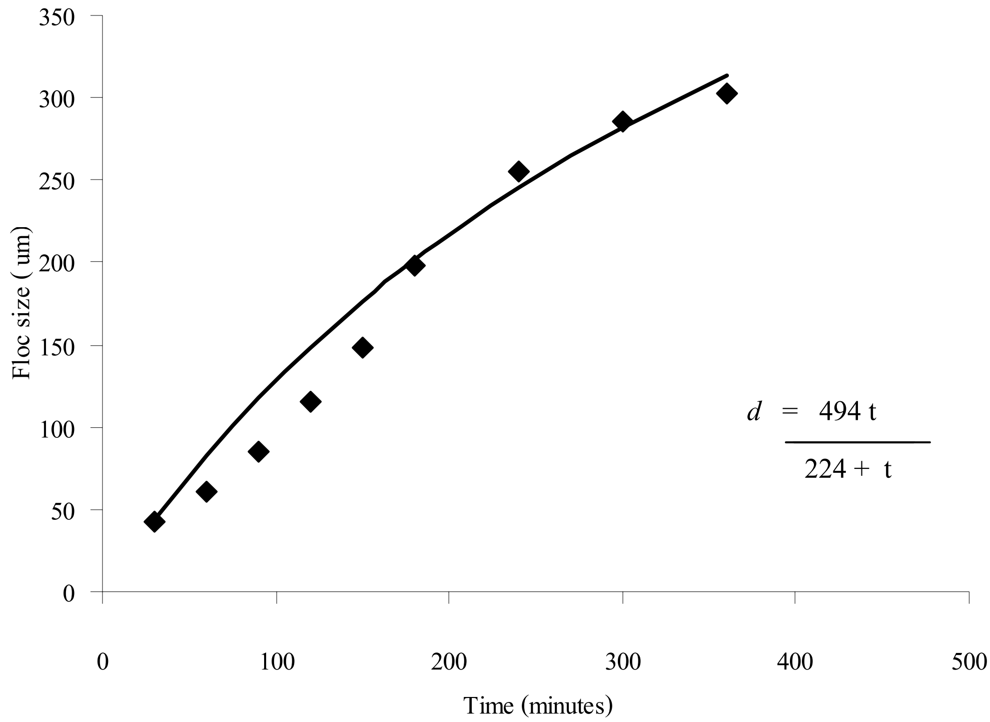
Appendix Figure E10 Maximum floc size at steady state (μm); d_S of run no.10



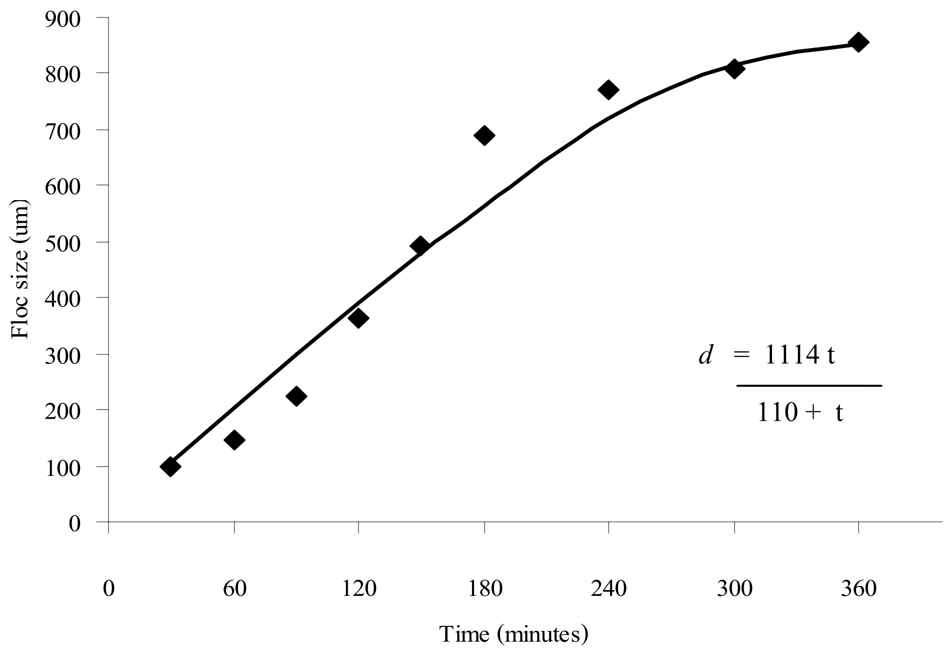
Appendix Figure E11 Maximum floc size at steady state (µm); d_S of run no.11



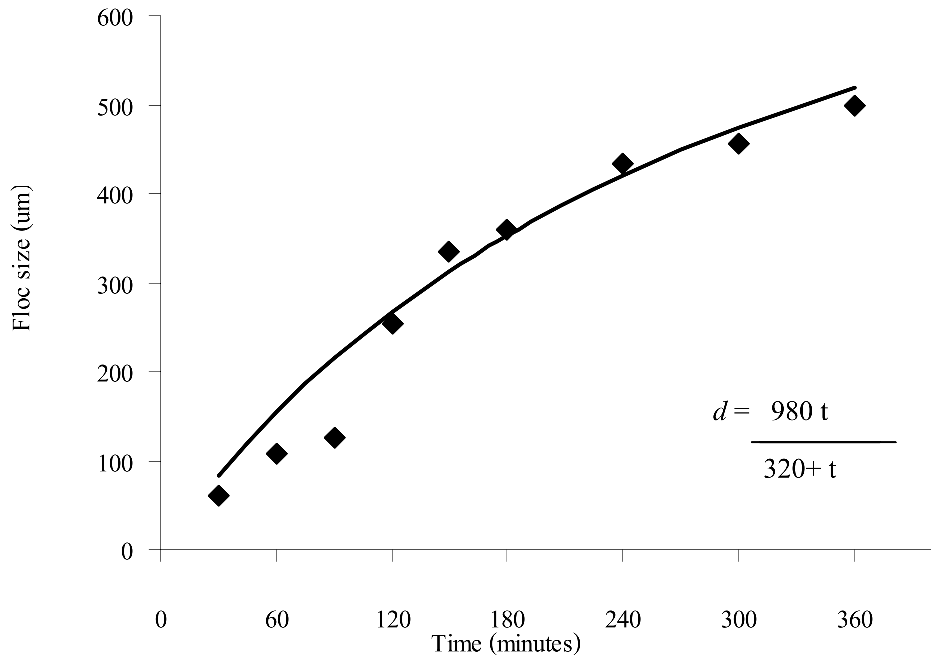
Appendix Figure E12 Maximum floc size at steady state (µm); d_S of run no.12



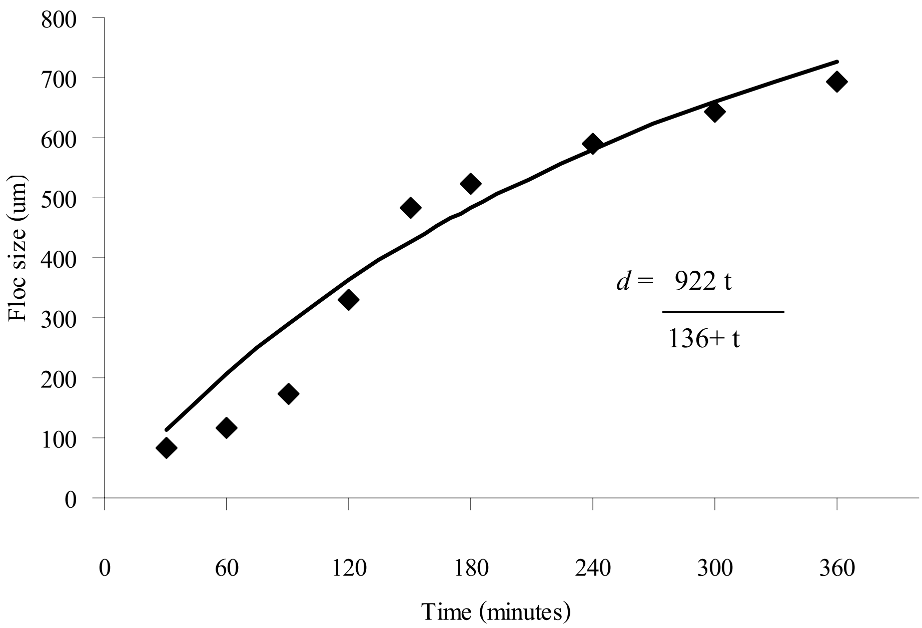
Appendix Figure E13 Maximum floc size at steady state (μm); d_S of run no.13



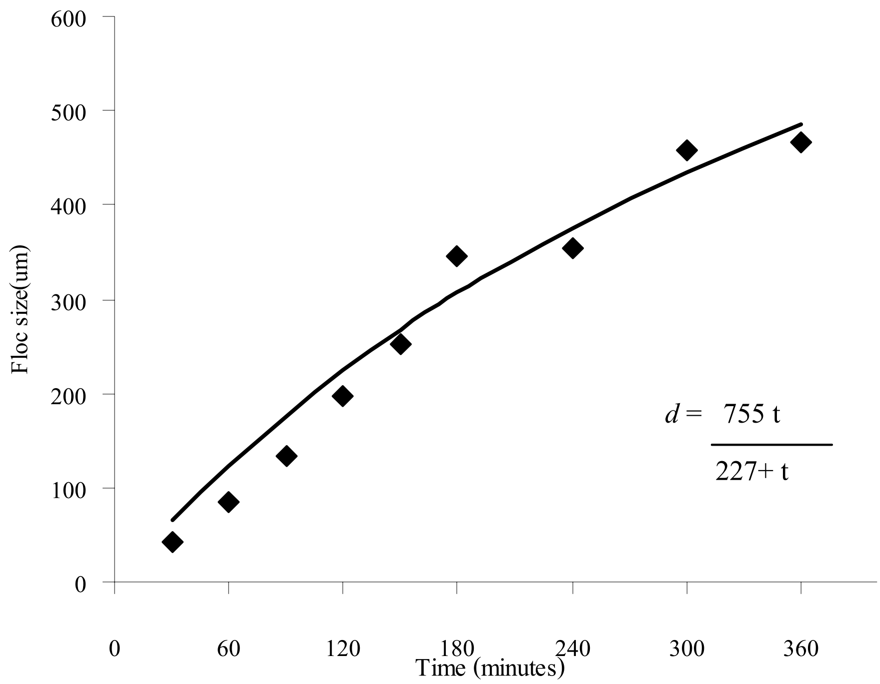
Appendix Figure E14 Maximum floc size at steady state (μm); d_S of run no.14



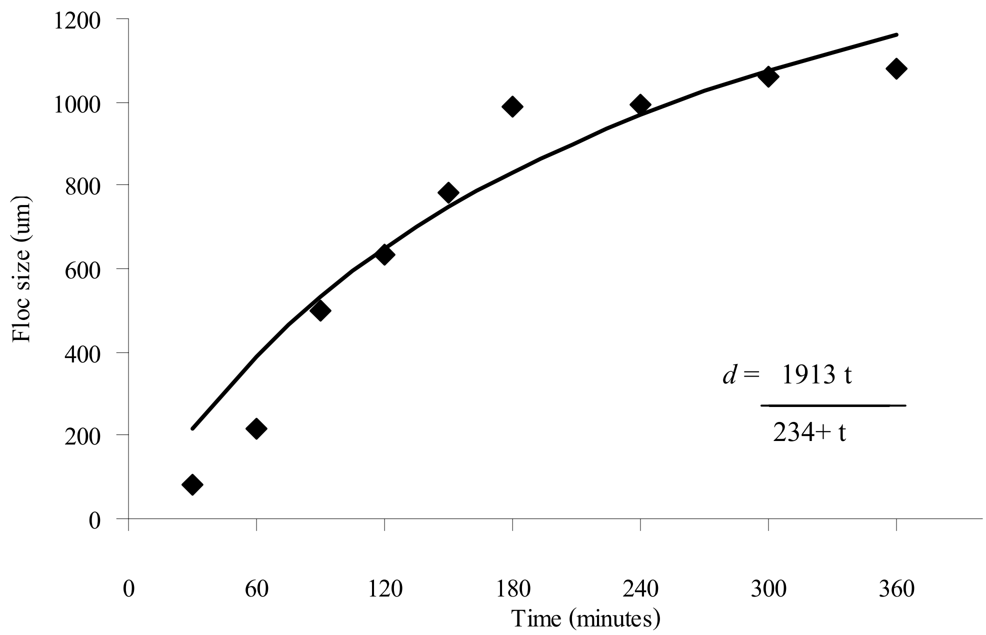
Appendix Figure E15 Maximum floc size at steady state (μm); d_s of run no.15



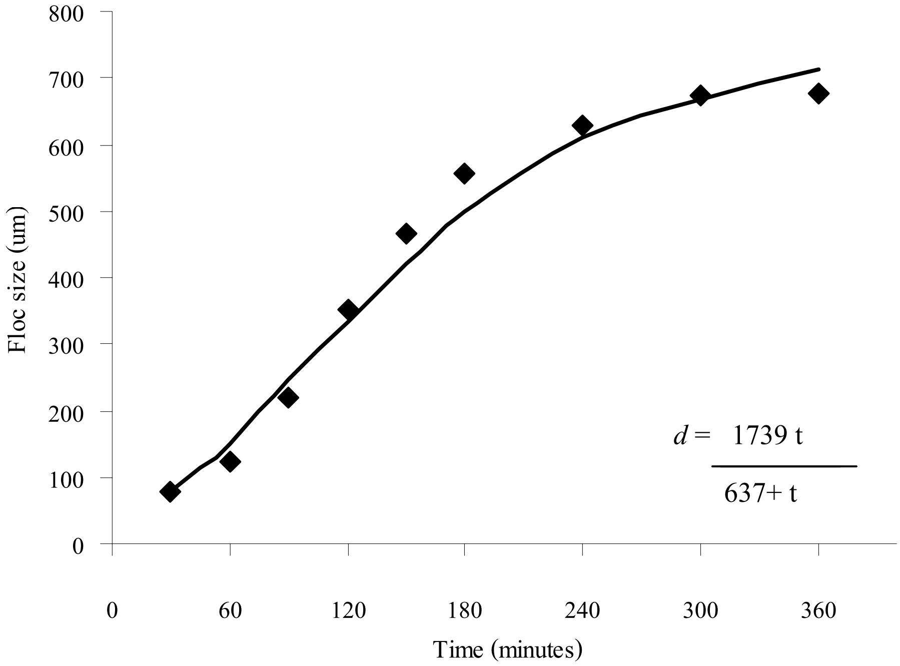
Appendix Figure E16 Maximum floc size at steady state (μm); d_s of run no.16



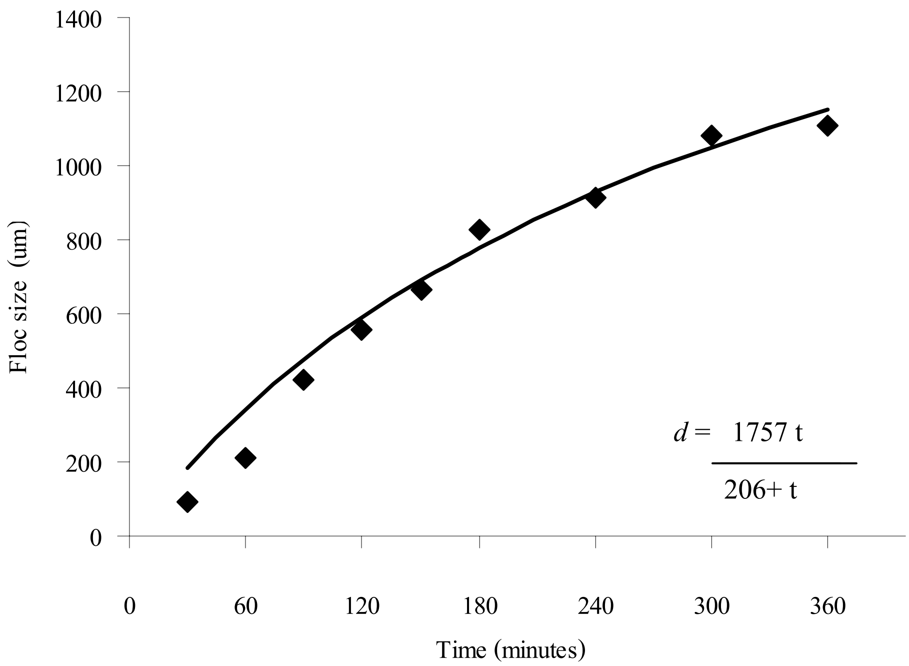
Appendix Figure E17 Maximum floc size at steady state (μm); d_S of run no.17



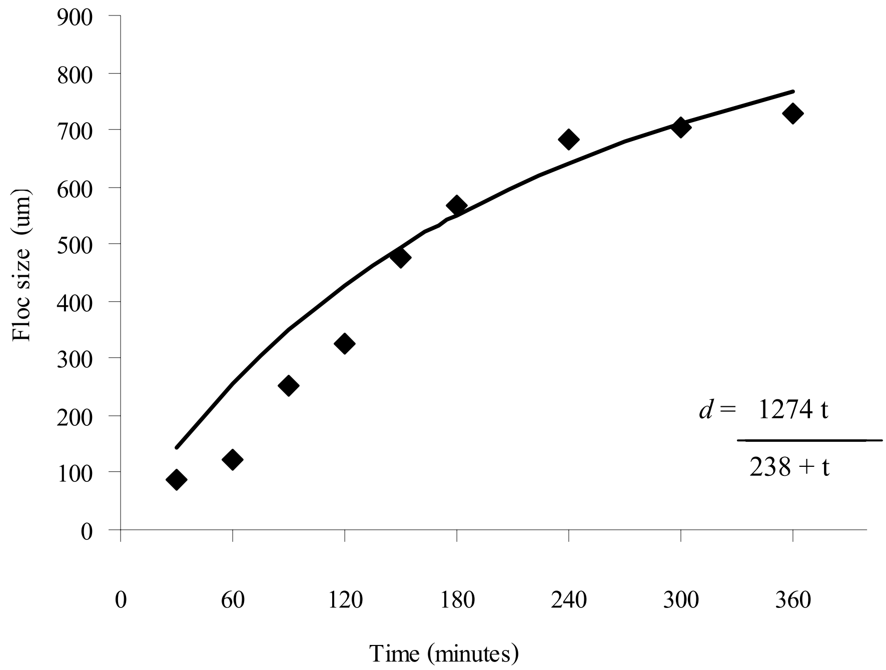
Appendix Figure E18 Maximum floc size at steady state (μm); d_S of run no.18



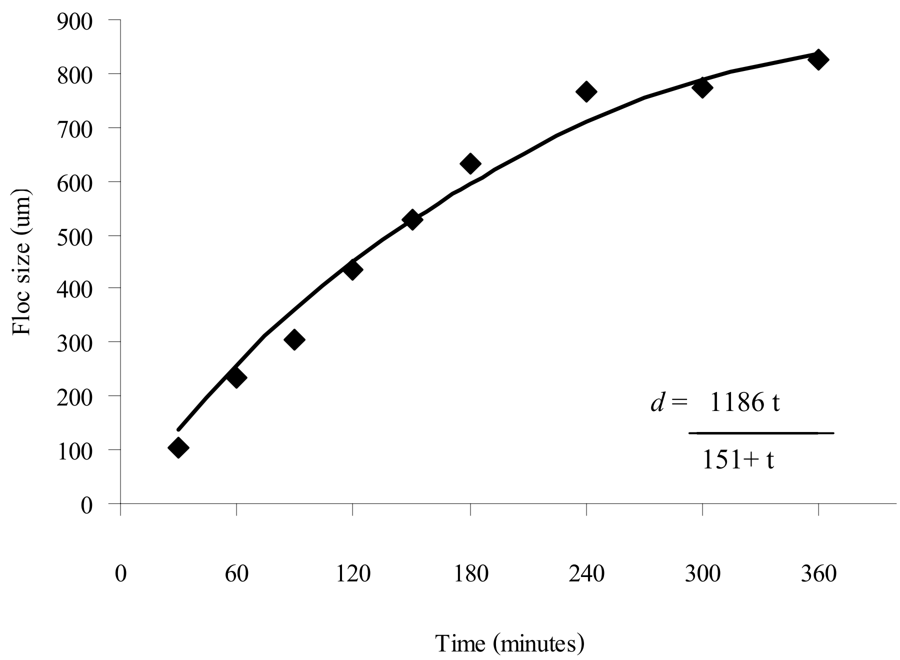
Appendix Figure E19 Maximum floc size at steady state (µm); d_s of run no.19



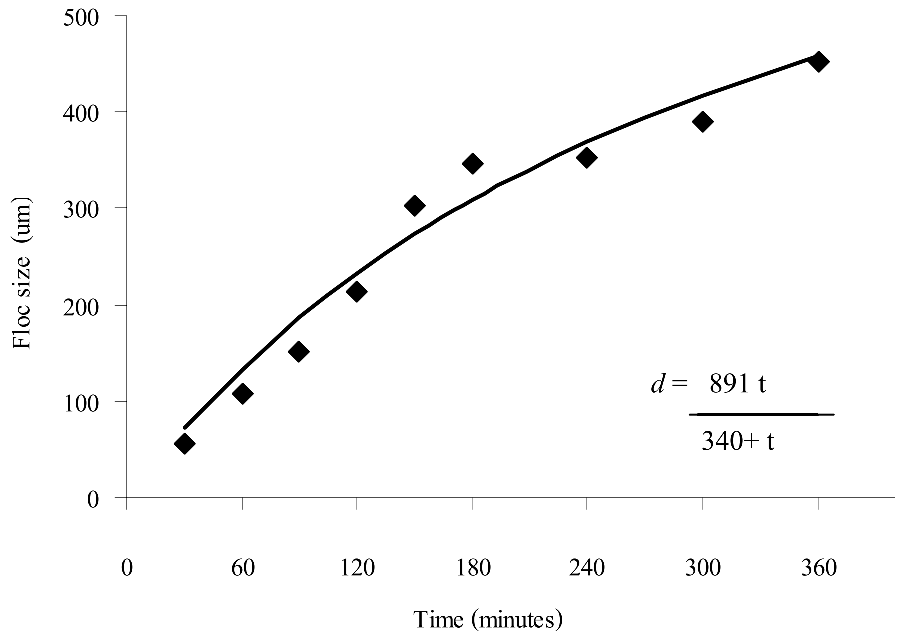
Appendix Figure E20 Maximum floc size at steady state (µm); d_s of run no.20



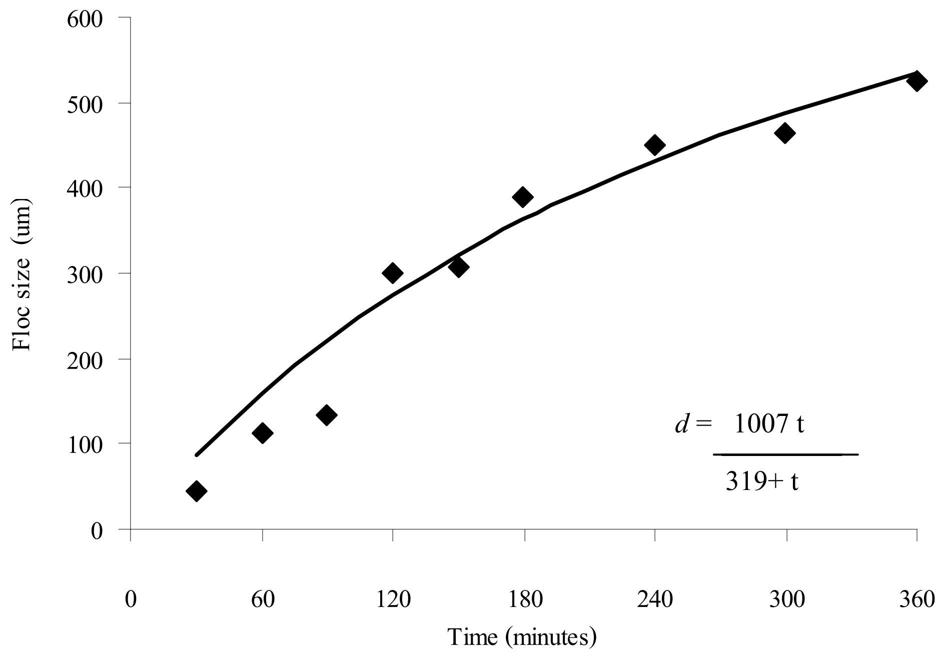
Appendix Figure E21 Maximum floc size at steady state (µm); d_S of run no.21



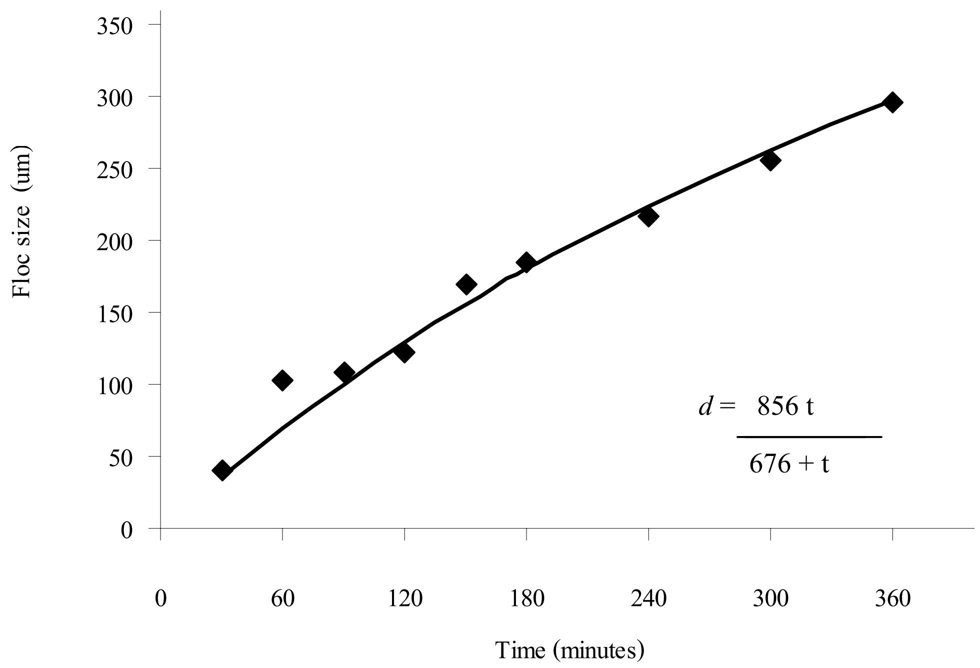
Appendix Figure E22 Maximum floc size at steady state (µm); d_S of run no.22



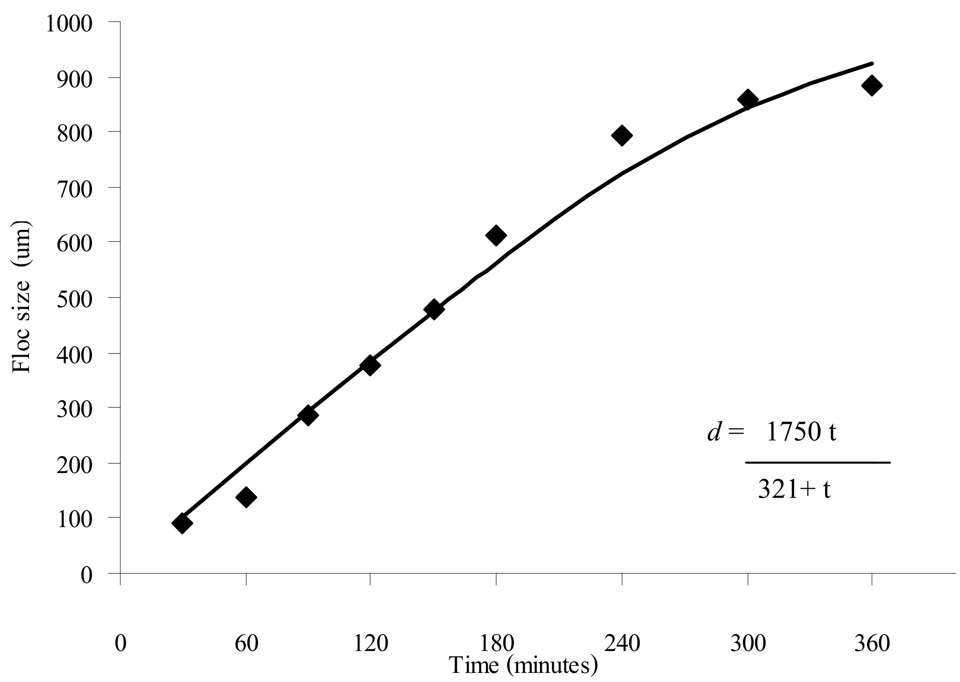
Appendix Figure E23 Maximum floc size at steady state (µm); d_S of run no.23



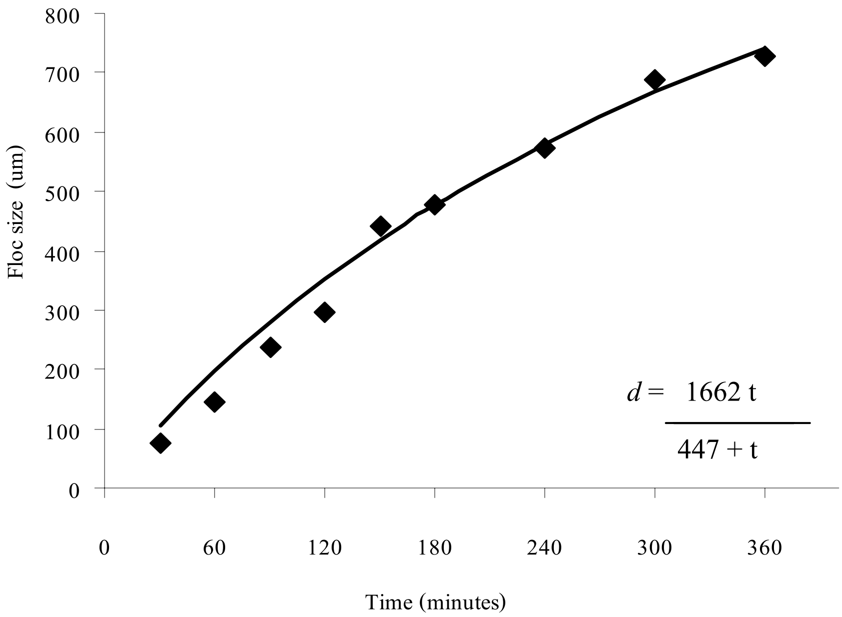
Appendix Figure E24 Maximum floc size at steady state (µm); d_S of run no.24



Appendix Figure E25 Maximum floc size at steady state (μm); d_S of run no.25



Appendix Figure E26 Maximum floc size at steady state (μm); d_S of run no.26



Appendix Figure E27 Maximum floc size at steady state (µm); d_S of run no.27