Effect of mixing on the kinetics of polymer-aided flocculation

Stephanie Young, Stephen J. Stanley and Daniel W. Smith

ABSTRACT

Polymer-aided flocculation is defined in this study as the coagulation and flocculation process which is accomplished by using alum in conjunction with a small dosage of polymer. Polymer is commonly used to improve flocculation performance; however, few in-depth studies of mixing requirements when using polymer as an aid have been reported. Presented is an evaluation of the effect of mixing on the kinetics of polymer-aided flocculation. The study found that the optimum $\overline{G}_f$-values occurred at 70 to 100 s^{-1}, such that $\overline{G}_f t_b$-values (Camp Number) were in the range of 113,000 to 144,000. The limited improvement in kinetics achieved by increasing the $\overline{G}_f$-value beyond 100 s^{-1} will probably not justify the higher energy consumption. Moreover, experimentation has shown that the maximum $\overline{G}_f$-value recommended for the design is $\overline{G}_f = 200$ s^{-1} ($\overline{G}_f t_b = 252,000$), and the critical mixing rate occurred at $\overline{G}_f = 400$ s^{-1} ($\overline{G}_f t_b = 432,000$), beyond which significant floc break-up will occur. The optimum $\overline{G}_f$-value determined from the study suggests that the currently designed flocculators using alum alone can be used when polymer is used as a coagulant aid. Thus, the use of polymer as a coagulant aid can improve the coagulation and flocculation efficiency in existing systems.

Key words | floc, flocculation, kinetics, mixing, polymer, size distributions

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INTRODUCTION

As concern with the delivery of high quality, safe water increases, regulatory authorities are setting lower limits for turbidity and micro-organisms. To achieve water with concentrations below these limits requires the removal of fine particulate matter less than 10 μm in size. These particles can be a source of contaminants that have been adsorbed on them, and be associated with pathogenic micro-organisms and viruses in raw water. The conventional method for the removal of particulate matter in water is coagulation, flocculation, sedimentation and filtration. Alum is often used as a coagulant in water treatment plants to aggregate particles. This is commonly done in a tapered mixing regime with a series of flocculators operated at $\overline{G}_f$ from 70 to 20 s^{-1}. The process results in weak flocs and an excessive volume of sludge, which is difficult to dewater (Yang 1996). The excessive volume of sludge increases the overall sludge disposal cost, and may constitute a possible ecological hazard if the sludge is dumped into rivers or lakes (Bosanac *et al.* 1993). A possible health concern, associated with the use of alum that has been overdosed, is residual aluminium concentrations in finished water (Martyn 1989).

In order to meet the more stringent drinking water guidelines and standards, water utilities and researchers have proposed a number of strategies to optimise coagulation and flocculation processes. One of the realistic and cost-effective strategies to address the above issue is to use coagulant alternatives, which can increase production effectiveness in existing systems. A number of coagulant alternatives are available, which include the use of: (1) a cationic metal-polysilicate complex; (2) inorganic polymer flocculants such as polymerised alum salts, high basicity or high OH/Al ratio polymerised aluminium salts, or (3) organic polymer flocculants either as the lone coagulant or as a coagulant aid. The use of an organic polymer as

a coagulant aid is one of the most cost-effective strategies to improve the removal of fine particulate matter.

The use of an organic polymer as a coagulant aid can provide a number of distinct advantages. First, it can increase the size, strength and density of flocs (Levine & Friesen 1987; Yang 1996). This leads to excellent removal of fine particles (Namasivayam & Kanagarathinam 1992). Greater particulate removal in the clarification process will result in improved filter performance. Second, it can reduce the size or number of flocculation and/or settling basins, as a result of the increase in flocculation and sedimentation rates. Third, it can lower alum dosage, and tends to reduce residual aluminium concentrations (Prendiville & Chung 1992). Finally, it can reduce sludge volume, and form sludge with better dewatering properties (Tascchi 1977; King & Blankenship 1979). This decreases the overall sludge disposal cost. Due to these benefits, it has become an effective method for drinking water treatment.

Although the use of polymers as coagulant aids offers many advantages, it has recently gained greater popularity in water treatment plants. Thus, specific operating conditions for using polymers as coagulant aids have not been widely reported, and operation conditions used are the same as for the alum flocculation process. This study presents an evaluation of mixing on the kinetics of polymer-aided flocculation. The information will aid the process design, control and optimisation for applications in water treatment plants.

THEORY

For the purposes of this study, a synthetic raw water made of kaolin in suspension with an optimum pH of 8.0, which was determined in this study, was used to simulate natural raw water. The synthetic raw water was buffered using 100 mg/l $NaHCO_3$. It was also treated by using alum in conjunction with a small dose of polymer.

The mechanism of polymer-aided flocculation at pH = 8 can be explained in that the negatively charged kaolin particles are destabilised by the positively charged intermediate hydrate species, such as Al^{3+}, $Al(OH)_2^+$ and $Al_{13}O_4(OH)_{24}^{7+}$, and then enmeshed on the precipitates of $Al(OH)_3^0(s)$, which result from the hydrolysis of alum and

form micro-flocs. The micro-flocs are bound by a long-chain polymer serving as a bridge. The polymer bridging ability is largely dependent on the length of the segment of polymer, and the conformation of the polymer chain, which are determined by mixing intensity. Historically, the mixing intensity has been controlled by the mean velocity gradient ($\overline{G}$). It was defined by Camp & Stein (1943) in terms of power input per unit volume:

$$\overline{G} = [P/\mu'V]^{\frac{1}{2}}, \tag{1}$$

where P is the total power dissipated (W), μ' is the absolute viscosity (Ns/m^2), and V is the volume of the tank (m^3). Equation (1) may also be expressed as:

$$\overline{G} = \left[\frac{\varepsilon}{\gamma}\right]^{\frac{1}{2}}, \tag{2}$$

where ε is the average rate of energy dissipation per unit mass (m^2/s^3), and γ is kinematic viscosity (m^2/s).

The destabilisation of the clay particles by the polymer bridging mechanism includes both adsorption and inter-particle bridging (Ruehrvein & Ward 1952; Michaelis 1954; Michaelis & Morellos 1955; La Mer *et al.* 1957; Healy & La Mer 1962; La Mer & Healy 1963; Kane *et al.* 1963; O'Melia 1987). The polymer adsorption is accomplished by: (1) transport of particles close to the polymer chain; (2) collision between particle and polymer; and (3) adhesion. As low bonding energy per segment suffices to render the affinity of the particle on the segment, most of the collisions result in adhesion. Collision and adherence are fast reaction processes, and hence the rate of polymer adsorption is governed by the transport processes. The primary mechanisms for transport are: (1) perikinetic flocculation driven by thermal forces; (2) orthokinetic flocculation due to bulk fluid and turbulent motions; and (3) differential settling due to larger particles overtaking smaller particles. The orthokinetic flocculation is the dominant mechanism in polymer-aided flocculation with mixing input. The rate of particle transport is dependent on the mixing intensity.

Mixing has an impact on the kinetics of polymer-aided flocculation through affecting the length of the segment of the polymer chain, the conformation of the long-chain

polymer, and the rate of collisions. Optimum mixing rates provide effective bridging, so that absorbed polymers extend far enough from the particle surface to attach to other particles, and also so that some free surface is available for adsorption of the extended segments. When mixing rates are higher than the critical mixing rate, break-up of the floc occurs. The break-up of the floc is contributed to by floc rupture (Francois 1987) and surface erosion (Argaman & Kaufman 1970). Floc rupture is due to pressure differences on opposite sides of the floc, which cause bulgy deformation and rupture. Surface erosion of primary particles from flocs is contributed to by shear stress that results from mixing. The generalised model for the floc break-up rate in orthokinetic flocculation (Amirtharajah & O'Melia 1990) takes the two break-up mechanisms of splitting and erosion into account, based on the existing models (Parker *et al.* 1972; Pandya & Spielman 1982). It gives the simplest expression of the rate of break-up function as:

$$\mathrm{d}n_1/\mathrm{d}t = K'_B \overline{G}^L, \qquad (3)$$

where K'_B is the floc break-up coefficient, and the exponent L is the constant, which value is dependent on the floc size. L has a value of 4 for unstable flocs greater than the micro-scale range, and equals 2 for flocs smaller than the micro-scale range (Amirtharajah & O'Melia 1990).

The above model shows: (1) floc break-up has zero-order kinetics with respect to the concentration of the primary particles; (2) mixing intensity is the major factor impacting on the rate of floc break-up; and (3) the rate of floc break-up increases as the $\overline{G}$-value increases in orthokinetic flocculation.

Theoretically, mixing has a significant impact on the kinetics of polymer-aided flocculation. The use of an optimum mixing rate will offer higher polymer bridging efficiency. Therefore, it is essential to evaluate the effect of mixing on the kinetics of polymer-aided flocculation, and to determine the optimum mixing rates.

EXPERIMENTAL METHODS

Flocculation experiments for the kinetic study were carried out in a standard 2 l square jar test apparatus (115 mm × 115 mm × 150 mm) with a 76 mm diameter flat-blade impeller, as described by Hudson & Wagner (1981). Synthetic raw water made of kaolin particles K_2-500 (Fisher Scientific Co.) with a 20 mg/l concentration was used to simulate natural raw water.

Before the coagulants were added, the synthetic raw water was brought to the optimum alkalinity condition using $NaHCO_3$, and then to the optimum pH of 8 using 1N HCl and 1N NaOH, and buffered using 100 mg/l $NaHCO_3$. Alum was added first, then the polymer solution was added in close proximity to the alum near the impeller to ensure complete dispersion. The experiments tend to evaluate the effect of mixing on flocculation (slow mixing stage, $\overline{G}_f$) rather than on destabilisation (rapid mixing stage, $\overline{G}_c$). A fixed $\overline{G}_c$ of 150 s^{-1} for 2 min was used to destabilise particles when $\overline{G}_f \leq 150$ s^{-1} was evaluated. Over 150 s^{-1} the single mixing stage ($\overline{G}_c = \overline{G}_f$) was used. The fixed flocculation time (t_f) of 30 min was used in each flocculation study, but the performance of flocculation was monitored every 3 min by analysing particle size distributions of the flocculated waters with a light-blockage Hiac/Royco Model 8000A particle size analyser. The particle size analyser employed a laser-light source along with advanced data acquisition and processing systems. The analyser was calibrated according to the manufacturer's specifications.

A series of jar tests was conducted to determine the optimum chemical conditions, which include the optimum pH, the alkalinity, the type of polymer, the dosage combination of alum and polymer, and the order of polymer addition in relation to when the alum was added. The final results are detailed elsewhere (Yang 1996). To summarise, it was found that the optimum pH was 8, and that the optimum alkalinity condition was achieved when the concentration of $NaHCO_3$ in the jar was 100 mg/l. The optimum chemical dose combination was found to be 5 mg/l of alum and 0.5 mg/l of non-ionic polymer (Percol LT20, Allied Colloids Inc.). The Percol LT20 consisted of polyacrylamides, which are a carboxyl-containing polymer with hydroxyl groups.

The effect of mixing on the kinetics of polymer-aided flocculation was evaluated under optimum chemical conditions. The kinetics of polymer-aided flocculation were characterised by the rate of flocculation and the rate of

floc growth. The rate of flocculation was evaluated by the variation of the primary particle concentration with time, and the rate of floc growth was evaluated by the variation of the mean floc size ($\overline{D}_{6.3}$) with time. $\overline{D}_{6.3}$ was calculated using Equation (4) (Alderliesten 1984):

$$\overline{D}_{6.3} = \left[\sum_i n_i D_i^6 / \sum_i n_i D_i^3\right]^{\frac{1}{3}}, \tag{4}$$

where D_i is the statistical value of the diameter. It can be expressed using the threshold settling data or the midpoint of each successive class-size interval in the particle size analyser.

The effect of mixing on the kinetics was evaluated by investigating the impact of mixing on the kinetic parameters which include: the first order rate constant (k), the floc build-up time (t_b), the maximum mean floc growth rate ($R_{(t_2 + t_1)/2})_{\max}$, and the critical flocculation time (t_o). Furthermore, the effect of mixing on the maximum mean floc diameter ($d_{\max}$) was evaluated to determine the critical $\overline{G}_f$-value, beyond which significant floc break-up occurs.

The methods of determination of the kinetic parameters and $d_{\max}$ are summarised below. The first order kinetic parameter (k) was determined from the flocculation curve of $\ln(n)$ versus t_f. It was confirmed in this study that the kinetics of polymer-aided flocculation follow the first order kinetic model based on the following assumptions: (1) the average vessel parameter $\overline{G}_f$ was the rate controlling factor; (2) orthokinetic flocculation dominated the mechanism of transport; (3) collisions occurred between the particles within the size range of 1 to 10 μm; (4) the instantaneous concentration of the primary particles was equal to the cumulative particle concentration within the size range of $d \leq 10$ μm, at that moment; and (5) the break-up of the floc was negligible when $\overline{G}_f \leq 400$ and $t_f \leq 30$ min. The model can be expressed as:

$$dn/dt_f = -kn, \tag{5}$$

where k is the first-order rate constant (min^{-1}), n is the cumulative concentration of primary particles with size equal to and less than 10 μm (counts/ml), and t_f is the flocculation time (min). The integral of the model being:

$$\ln(n) = -k\,t_f + c, \tag{6}$$

where c is the constant. The slope of the straight line of $\ln(n)$ versus t_f gives the value of the first-order kinetic constant (k).

The floc build-up time (t_b) was determined from the floc growth curve of $\ln\overline{D}_{6.3}$ versus t_f. It was found in this study that the mean size of polymeric floc increased exponentially with t_f (Yang 1996):

$$\overline{D}_{6.3} = (\overline{D}_{6.3})_0 e^{\mu t_f}, \tag{7}$$

here $\overline{D}_{6.3}$ is the mean floc diameter (μm), $(\overline{D}_{6.3})_0$ is the initial mean floc diameter (μm), t_f is the flocculation time (min), and μ is the floc growth constant (min^{-1}).

By plotting $\overline{D}_{6.3}$ versus t_f, t_b was determined to be the time when the floc reached critical size ($d_{\max}$). The floc build-up time (t_b) is a simple, convenient parameter used to evaluate the overall rate of floc growth. This is because t_b includes all the factors which affect the rate of floc growth, and can be used to compare various process conditions.

The maximum mean floc growth rate was determined from a plot of the mean floc growth rate curve of $R_{(t_2 + t_1)/2}$ against $(t_2 + t_1)/2$ where the mean floc growth rate $R_{(t_2 + t_1)/2}$ was calculated by:

$$R_{(t_2 + t_1)/2} = \frac{(\overline{D}_{6.3})_{t_2} - (\overline{D}_{6.3})_{t_1}}{t_2 - t_1}, \tag{8}$$

where $R_{(t_2 + t_1)/2}$ (μm/min) was the mean polymeric floc growth rate at the mean flocculation time $(t_2 + t_1)/2$ (min); $(\overline{D}_{6.3})_{t_2}$ (μm) and $(\overline{D}_{6.3})_{t_1}$ (μm) were the mean floc diameters at the flocculation times of t_2 and t_1 (min), respectively.

RESULTS AND DISCUSSION

Figures 1 to 4 illustrate the importance of mixing to polymer-aided flocculation. Figure 1 presents the impact of mixing on the rate of polymer-aided flocculation where k is a first order rate constant. Two models presented in Equations (9) and (10) were tested in an attempt to describe the effect of mixing on k at $20 \leq \overline{G}_f \leq 400$ s^{-1}.

$$k = 7.967\,(\overline{G}_f)^{0.004} - 8.048 \text{ [counts/(ml} \cdot \text{min)]}$$
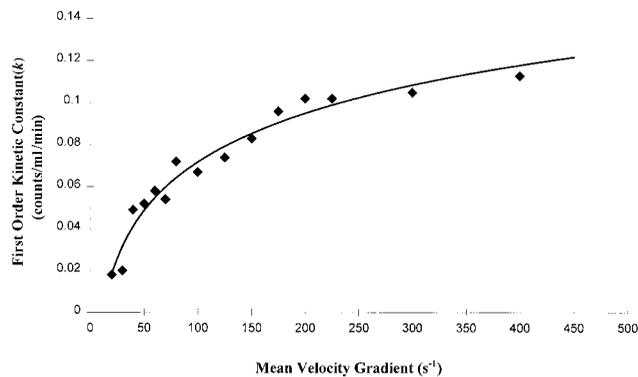$$20 \leq \overline{G}_f \leq 400 \text{ s}^{-1}. \tag{9}$$

Figure 1 │ Effect of mixing on first order kinetic constant (k).

Figure 2 │ Effect of mixing on floc build-up time (t_b).

$$k = 0.033 \ln (\overline{G}_f) - 0.082 \ [\text{counts}/(\text{ml} \cdot \text{min})]$$
$$20 \le \overline{G}_f \le 400 \ \text{s}^{-1}. \tag{10}$$

The model simulations and residual examinations demonstrated that these two models predicted the impact of mixing on k with the same precision. Therefore, both models could be used to predict the impact of mixing on the rate of polymer-aided flocculation.

Figure 1 shows that the curve tends to be linear when $\overline{G}_f \le 200 \ \text{s}^{-1}$, and it approaches a uniform value when $\overline{G}_f > 200 \ \text{s}^{-1}$. This indicates that an increase in $\overline{G}_f$ above $200 \ \text{s}^{-1}$ is not an effective method of improving the performance of flocculation. The relationship between $\overline{G}_f$ and k was approximated by the linear model ($R^2 = 0.875$) in the range of $20 \le \overline{G}_f \le 200 \ \text{s}^{-1}$:

$$k = 0.00041\overline{G}_f + 0.024. \tag{11}$$

Similarly, the relationship shown in the literature, based on alum coagulation and flocculation (Argaman & Kaufman 1968; Amirtharajah & O'Melia 1990), is:

$$k = k_A \overline{G}_f, \tag{12}$$

where the ratio constant (k_A) was termed the overall flocculation constant.

Both Equations (11) and (12) show that the first order rate constant was directly proportional to $\overline{G}_f$ at a low mixing rate when floc break-up was not significant. At a higher rate $\overline{G}_f \le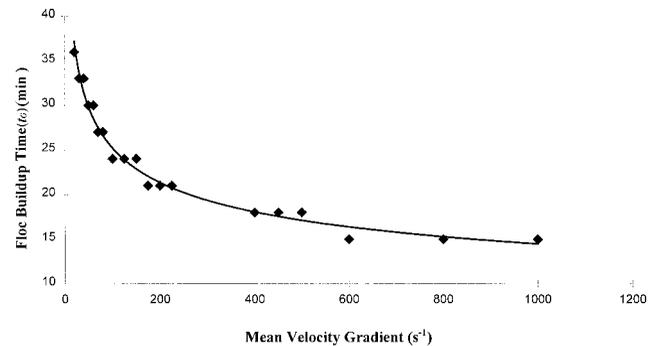 200 \ \text{s}^{-1}$ the flocculation rate increases, but not at the same rate. This is due to the fact that the break-up starts to become a significant factor. The comparison of the two equations has also led to the conclusion that polymer-aided flocculation, and alum coagulation and flocculation, could be represented by the same type of kinetic model. The role of polymer in the flocculation process was to bridge the fine flocs, resulting in bigger and denser flocs that hastened the rate of sedimentation. In addition, the $\overline{G}_f$-values were significantly higher than those reported for alum alone.

Figure 2 indicates the impact of mixing on the overall rate of polymeric floc growth evaluated by the floc build-up time (t_b). The t_b is the time required for the floc to reach the maximum size. A mathematical model has been developed which quantitatively describes the correlation between t_b and $\overline{G}_f$:

$$t_b = -5.702 \ln(\overline{G}_f) + 52.062 . \tag{13}$$

The model simulation and residual examination process have indicated that the model fits the data. It has been found that the model residuals were independent with a zero mean and a constant variance. Thus, the model was adequate and can be used to predict the effect of mixing on the rate of polymeric floc growth.

Figure 2 shows that t_b decreased significantly with $\overline{G}_f$ at $\overline{G}_f \le 200 \ \text{s}^{-1}$, but only slightly at $\overline{G}_f > 200 \ \text{s}^{-1}$. The conclusion was consistent with that derived from the analysis of the impact of mixing on the first order rate constant (k). Both analyses confirm the same result, that
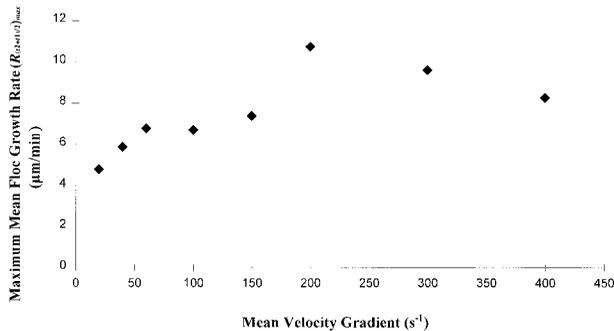
Figure 3 | Effect of mixing on maximum mean floc growth rate $(R_{(t_2+t_1)/2})_{max}$.

Figure 4 | Effect of mixing on critical flocculation time (t_o).
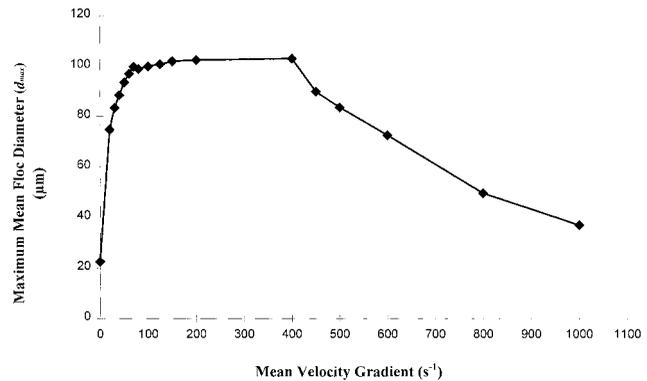
Figure 5 | Effect of mixing on the maximum mean floc diameter (d_{max}).

the rate of floc growth and the rate of flocculation were increased by raising the value of $\overline{G}_f$ in the range of $\overline{G}_f \leq 200$ s^{-1}. However, little improvement in performance occurred when $\overline{G}_f > 200$ s^{-1}.

Figure 3 demonstrates the impact of mixing on the maximum mean floc growth rate $(R_{(t_2+t_1)/2})_{max}$. It has been found that $(R_{(t_2+t_1)/2})_{max}$ increases when there is an increase in the $\overline{G}_f$-value up to 200 s^{-1}, and decreases when $200 < \overline{G}_f \leq 400$ s^{-1}. Therefore, the maximum value of $(R_{(t_2+t_1)/2})_{max}$ occurred at $\overline{G}_f = 200$ s^{-1}. The results confirm that the first order rate constant (k) tends to increase slowly and floc build-up time (t_b) tends to decrease slowly at $200 < \overline{G}_f \leq 400$ s^{-1}, as previously discussed.

Figure 4 presents the effect of mixing on the critical flocculation time (t_o), which was used to characterise the variation rate of the mean floc growth rate $(R_{(t_2+t_1)/2})$. It was found that t_o decreased non-linearly with the increase in $\overline{G}_f$ at $0 < \overline{G}_f \leq 400$ s^{-1}. The non-linear regression was performed to quantitatively describe the correlation between t_o and $\overline{G}_f$. The model residual examination process showed that the model was adequate. Thus, the impact of $\overline{G}_f$ on t_o could be predicted by:

$$t_o = 87.101 \, (\overline{G}_f)^{-0.163} - 30.752 , \tag{14}$$

where t_o was the elapsed time required for the very first fine flocs to appear, and was directly proportional to the floc appearance time. However, t_b, as discussed, was the time when d_{max} was reached. Comparison of Figure 3 with
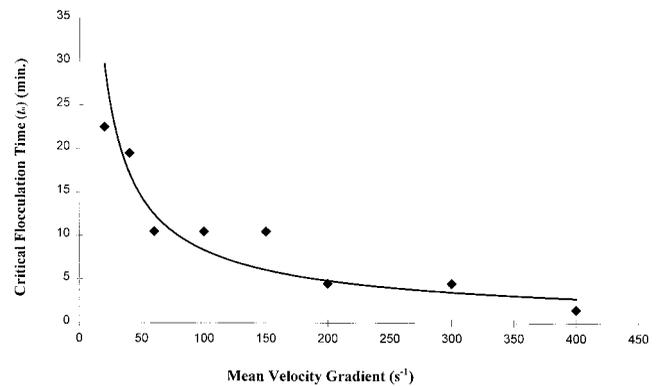
Figure 4 has led to the conclusion that $\overline{G}_f$ had a consistent impact on the floc build-up time (t_b) and the critical flocculation time (t_o).

In conclusion, the analyses of the impact of $\overline{G}_f$ on the first order rate constant (k), the maximum mean floc growth rate $(R_{(t_2+t_1)/2})_{max}$, the floc build-up time (t_b), and the critical flocculation time (t_o), all point to the same conclusion that the kinetics of polymer-aided flocculation increased significantly with $\overline{G}_f$ at $\overline{G}_f \leq 200$ s^{-1}, and only slightly at $200 \mu \overline{G}_f \leq 400$ s^{-1}. As a result, the kinetics of polymer-aided flocculation were controlled by mixing intensity at $\overline{G}_f \leq 200$ s^{-1}.

Figure 5 presents the effect of mixing on maximum mean floc diameter (d_{max}). The d_{max} is the equilibrium size in the stabilisation stage of the floc growth process $(t_f > t_b)$. It is determined by two opposing factors: the mechanical

strength of the floc, and the applied breaking forces. The mechanical strength is contributed to by chemical bonds, hydrogen bonds, van der Waals attraction, and bridging. The breaking forces include the shearing force and the pressure force. The size of the floc reaches $d_{\max}$ as the equilibrium between these two opposing forces is established. Figure 5 shows that $d_{\max}$ is controlled by mixing intensity only at $\overline{G}_f \leq 70$ to $100\ s^{-1}$. The value of $d_{\max}$ reaches its maximum value from $\overline{G}_f = 70$ to $100\ s^{-1}$ up to $\overline{G}_f = 400\ s^{-1}$. It decreases sharply at $\overline{G}_f > 400\ s^{-1}$ due to the significant break-up of flocs.

The analysis of Figures 1 to 5 indicates that when $\overline{G}_f = 100$ to $200\ s^{-1}$ the increase in $\overline{G}_f$ will not subsequently increase $d_{\max}$. Whereas it will increase the kinetics of flocculation and this will decrease the required flocculation time and increase the overall treatment efficiency. However, the improvement in kinetics achieved by increasing the $\overline{G}_f$-value from $\overline{G}_f = 100\ s^{-1}$ to $\overline{G}_f = 400\ s^{-1}$ will probably not justify the higher energy consumption, although a shorter flocculation time is required when using a higher $\overline{G}_f$-value.

SUMMARY AND CONCLUSIONS

The principle objectives of the study were to evaluate the importance of mixing to polymer-aided flocculation, and to determine the optimum mixing rate when polymer was used as a coagulant aid. The significant findings of this study were based on the Hudson's jar tests and a unique combination of synthetic raw water, alum, polymer and particle size analyser. The conclusions were determined through the evaluation of mixing on the kinetic parameters, and on the maximum mean floc diameter. The conclusions are:

1. mixing has a significant impact on the kinetics of polymer-aided flocculation when $\overline{G}_f \leq 200\ s^{-1}$, especially when $\overline{G}_f$ is in the range of $20 \leq \overline{G}_f \leq 70$ to $100\ s^{-1}$;

2. mixing has a significant impact on $d_{\max}$ at $20 \leq \overline{G}_f \leq 70$ to $100\ s^{-1}$, but only slightly at $100 < \overline{G}_f < 400\ s^{-1}$, so it is not worthwhile to attempt

to increase $d_{\max}$ by raising $\overline{G}_f$ to a value greater than $100\ s^{-1}$ due to the higher energy consumption;

3. mixing has a slight impact on the kinetics of polymer-aided flocculation at $200 < \overline{G}_f < 400\ s^{-1}$, so it is not worthwhile to attempt to increase the kinetics by raising $\overline{G}_f$ to a value greater than $200\ s^{-1}$ due to the higher energy consumption;

4. for the system studied the optimum $\overline{G}_f$-values occurred at 70 to $100\ s^{-1}$ ($\overline{G}_f\, t_b = 113{,}000$ to $144{,}000$), the maximum $\overline{G}_f$-value recommended for the design is $200\ s^{-1}$ ($\overline{G}_f\, t_b = 252{,}000$), the critical $\overline{G}_f$-value occurs at $\overline{G}_f = 400\ s^{-1}$ ($\overline{G}_f\, t_b = 432{,}000$), and break-up of the floc is significant when $\overline{G}_f > 400\ s^{-1}$;

5. the optimum mixing rate required in polymer-aided flocculation ($\overline{G}_f = 70$ to $100\ s^{-1}$) is higher than that of alum flocculation where the optimum mixing rate is $\overline{G}_f = 40\ s^{-1}$, which was determined through experimentation within this study (Yang 1996).

The significance of this work is to demonstrate the role of mixing in polymer-aided flocculation. The study also shows that the use of polymer as a coagulant aid strengthens the flocs, which will eliminate the use of a tapered mixing regime that requires a series of flocculators. This would lead to less capital cost than when alum is used alone. The optimum $\overline{G}_f$-value determined from the study also suggested that the currently designed flocculator, for flocculation using alum only, can still be used when polymer is used as a coagulant. Thus, the use of polymer as coagulant aid can improve the coagulation and flocculation efficiency in the existing system.

It is acknowledged that there is an inconsistent $\overline{G}_f$-value in the jars. The possibility of changing the $\overline{G}_f$-value in the course of flocculation was extensively studied by one of the authors of this paper (Stanley 1995). In addition, the grid mixing system, which would provide homogeneous $\overline{G}_f$-values, was investigated by another PhD student in the department (Liem 1998). As the results were not available during the time this study was conducted, the kinetic study was based on the assumption that mixing was isotropic, and the average vessel parameter $\overline{G}_f$ was used to control the mixing rate. It should be pointed out that the results did not include the impact of local

hydrodynamics (especially in the impeller zone) and fluid flow patterns induced by different flocculation impellers at different mixing intensities. Moreover, care should be taken when the optimum $\overline{G}_f$ or $\overline{G}_f t_b$-values are used in the design as determined in the 2 l Hudson's jar test. This is because the performance of flocculation deteriorated with the increased size of the flocculator because of the variation of the fluid impeller mechanism, even when the $\overline{G}_f$-value was held constant (Stanley 1995). Therefore, it is important to search for another parameter to use as a scale-up criterion. This is currently being studied by Stanley (1995) and other researchers. Scale-up flocculation experiments are suggested to simulate full-scale applications.

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