Changes in the two-dimensional and perimeter-based fractal dimensions of kaolinite flocs during flocculation: a simple experimental study
Zhongfan Zhu, Dingzhi Peng and Jie Dou

ABSTRACT
In this study, Couette flow experiments were performed to estimate the temporal evolution of the 2D and perimeter-based fractal dimension values of kaolinite flocs during flocculation. The fractal dimensions were calculated based on the projected surface area, perimeter length and length of the longest axis of the flocs as determined by sampling observation and an image-processing system. The 2D fractal dimension, which relates the longest axis length and projected surface area of flocs, was found to decrease with the flocculation time, corresponding to the production of some porous flocs from the flow shear. This fractal dimension finally reached a steady state, which resulted from a dynamic equilibrium among the floc growth, floc breakage and floc restructuring. The perimeter-based fractal dimension, which characterizes the relationship between the projected surface area and the perimeter of flocs, increases with flocculation time because the flow shear increases the collisions among the primary particles, and some irregular flocs are formed. The perimeter-based fractal dimension reaches a steady level because of the balance among floc aggregation, breakage and restructuring. In addition, a stronger turbulent flow shear makes the steady state of fractal dimensions occur early during flocculation.

Key words | Couette flow, flocculation, fractal dimension, kaolinite, turbulent flow

INTRODUCTION
Fine-grained sediments, which carry static charges on their surfaces, have complicated electro-chemical and biological-chemical properties (Son & Hsu 2008). When these sediments move into estuarine and coastal areas, where turbulent motions can cause particles to collide, they can flocculate into flocs of varying sizes through the binding of primary particles. However, the turbulent flow shear may disrupt these porous and fragile flocs and result in small flocs and/or primary particles (Dyer 1989). The flocculation of cohesive fine-grained sediment is responsible for the evolution of floc size distribution, variations in floc structure, and, consequently, the settling velocities of flocs. Since the transport rate of fine-grained sediment is a function of the floc size and settling velocity, sediment flocculation plays an important role in causing the morpho-dynamic changes of estuarine and coastal zones through the complex process of sediment transportation, deposition, erosion, and consolidation (Maggi 2007).

Turbulence-caused flocculation has been investigated by many researchers using mathematical modelling (analytical methods and/or numerical simulations), field observation and laboratory experiments (Winterwerp 1998; Markussen & Andersen 2014). These works focused on two main perspectives: the floc size distribution and the floc structure. In these studies, an important aspect is that the concept of fractal geometry has been widely adopted to describe the floc structure. When the floc (formed in a water-sediment mixture) is treated as a self-similar fractal object, its properties (such as mass, volume and density) should scale as a power of its characteristic size (the exponent is termed the 3D fractal dimension $D_3$); thus, this fractal dimension is a measure of how primary particles fill the entire space of the floc (Serra & Casamitjana 1998).

Although many studies using fractal theory have provided insights into the flocculation process of cohesive sediment in a flow shear environment, some studies have
used a fixed value for the 3D fractal dimension to describe the dynamic flocculation process from the initial state to the steady/equilibrium state (Serra & Casamitijana 1998; Winterwerp 1998; Zhang & Li 2003). For example, based on a collision frequency function and a floc breakage function, Winterwerp (1998) developed an analytical model using a linear combination of formulae for aggregation and floc breakage to describe the temporal variation of the median floc size during the turbulence-caused flocculation. Nevertheless, a fixed value of the mean fractal dimension (such as 2 or 2.2) has been used in this model for simplicity. Moreover, some studies simply used $D_3$ as a constant in modelling fractal flocs during the dynamic transition of the floc population from non-equilibrium to the steady state (Zhang & Li 2003). Whether the use of a constant fractal dimension is applicable to the complete flocculation process is highly questionable. At the beginning of flocculation, there are only primary particles; fewer flocs are present, which implies that the averaged fractal dimension should be near the theoretical value of 3. In later flocculation stages, some porous and irregularly structured flocs develop, and fewer primary particles are present. In this case, the fractal dimension should be smaller than 3. Therefore, the flocculation model may require a variable fractal dimension to better understand the flocculation kinematics of suspended cohesive sediment in a flow shear environment.

Several experiments have quantified the evolution of the fractal dimension during flocculation, with conflicting results. Based on some published works, Khelifa & Hill (2006) suggested that the fractal dimension will decrease as the floc size increases during turbulence-induced flocculation process, and further presented a power law to describe the relationship between fractal dimension and floc size. A similar power law relationship was also derived in Maggi (2007) by laboratory optical observation of floc structure. This relationship has been adopted by some authors to modelling the turbulence-induced flocculation process (Maggi et al. 2007; Son & Hsu 2008; Byun et al. 2015; Shen & Maa 2015; Shin et al. 2015). Based on laboratory observation results, Kumar et al. (2010) made a simple modification to this relationship, and proposed an alternative model for a variable fractal dimension during flocculation. Different from the above-mentioned relationship, Vahedi & Gorczyca (2012) introduced a normal distribution of fractal dimension for a given floc size. However, in some published studies, a fixed constant value for the fractal dimension was still adopted to model the flocculation process. Xu et al. (2008) developed a size-resolved flocculation model to simulate the variations in floc size and suspended sediment concentration distribution by incorporating the fixed fractal dimension being 2, and comparing with published experimental data showed the validity of the model. A fixed fractal dimension value (being 2) was also used in Keyvani & Strom (2014) for modelling flocculation process in cycles of high and low turbulent shear, and a good agreement between the calibrated model and experimental data was presented. Mietta et al. (2011) also adopted a fixed fractal dimension incorporated into population balance equation model to simulate the behaviour of mud floc size distribution during flocculation. The fixed fractal dimension value could also be found in numerical experiments of Shen & Maa (2015). A sensitivity analysis of variable fractal dimension to the flocculation model has been performed in Cottereau et al. (2014). Additionally, some experimental studies reported the changes in fractal dimension during shear-induced flocculation (Bubakova et al. 2013; Nan et al. 2016; Moruzzi et al. 2017; Wang et al. 2017).

Despite these experimental results, it remains unclear how the fractal dimensions of flocs change during the flocculation process. Furthermore, the relationship between the changes in the fractal dimensions of flocs and the dynamic process of flocs during the flocculation process, which includes floc aggregation, floc breakage and floc restructuring, remains unclear. The main object of this study is to provide more experimental evidence on the temporal evolutions of the fractal dimensions of sediment flocs during the flocculation experiment. More importantly, we attempt to provide some descriptive physical insights about the relationship between the fractal dimension and the flocculation process. These findings may be helpful for further development of the flocculation model, which is always used to understand the transport kinematics of suspended cohesive sediment in estuarine and coastal waters. Section 2 briefly introduces the fractal dimensions and experimental arrangement. The temporal variations of fractal dimensions during flocculation are analysed in section 3. Finally, section 4 presents two simple concluding remarks.

**METHODS**

**Fractal dimension**

For the floc with a fractal structure, its volume $V$ can be related to the characteristic length of the floc, which is generally considered to be the length $L$ of the longest axis of the floc or the major axis length, in terms of the 3D fractal
dimension $D_3$, as follows (Serra & Casamitjana 1998): $V \propto L^{D_3}$, where $D_3$ characterizes the space-filling ability of the floc and its compactness, as introduced, and $D_3$ is 1–3. Similarly, the relationship between the projected surface area of the floc ($A$) and its longest axis length ($L$) can be assumed to satisfy the following power-law relation:

$$A \propto L^{D_2}$$

(1)

where $D_2$ is the 2D fractal dimension defined to relate the longest axis length to the projected surface area of the floc in a two-dimensional projected plane (Serra & Casamitjana 1998). When the floc is a simple sphere, $D_2$ is equal to 2. A high fractal dimension value is observed in compact and less porous flocs, whereas loose, large and highly branched flocs always have a low fractal dimension (Serra & Casamitjana 1998; Stone & Krishnappan 2003; Bubakova et al. 2013).

In some studies, the geometry of the floc was evaluated using the perimeter-based fractal dimension $D_{pf}$ as follows:

$$A \propto P^{2/D_{pf}}$$

(2)

where $D_{pf}$ was defined to characterize the relationship between the perimeter and the projected surface area of the floc in a projected plane (Serra & Casamitjana 1998; Stone & Krishnappan 2003). The value of $D_{pf}$ ranges from 1 for a spherical particle (a circle in the projected plane) to 2 for a linear aggregate (e.g. a chain of particles). Values of $D_{pf}$ larger than 1 show that with the increase in the projected area of the floc, the floc perimeter increases more rapidly than a simple sphere (for which $D_{pf}$ is 1) such that the floc boundary becomes more convoluted and more irregular (Spicer et al. 1996; Stone & Krishnappan 2003; Bubakova et al. 2015).

**Experimental introduction**

**Turbulent flow apparatus**

A Couette flow system was used to model the flow shear environment, as it can yield a more isotropic turbulent motion than other apparatuses such as oscillating grids and stirred blade impellers (Spicer & Pratsinis 1996; Serra & Casamitjana 1998; Cuthbertson et al. 2010). The system consisted of an inner Plexiglas cylinder of 150 mm in radius and an outer Plexiglas cylinder of 236 mm in radius; both cylinders were 682 mm high.

The outer cylinder was fixed, and the inner one was driven by a speed-adjusting motor (a 180 Watt three-phase motor, produced by the Beijing Orient Drive Industry Corporation, China) with three speed-reducing boxes and angular velocities $\omega$ of 24, 27, 60, 90, 120 and 180 revolutions per minute (rpm). Flocculation occurred between both cylinders. This sequential angular velocity order was selected based on two aspects. It is a result of different combinations of velocity scales provided by the speed-adjusting motor and scales of the speed-reducing boxes. Furthermore, these velocity values can correspond to different turbulent flow environments to analyse the fractal dimension characteristics in a turbulent flow, as follows.

**Flow field**

An acoustic Doppler velocity (ADV) meter equipped with three probes (velocity: 1–2.5 m/s; accuracy: 0.1 mm/s, with a standard deviation of 1%; produced by SonTek Corporation, USA) was used to measure the flow field of the Couette flow system. The three probes of the ADV can measure the radial, tangential and vertical components of the velocity in the Couette flow system. Because of the dimensional limitations of ADV probes and the gap between the outer and inner cylinders, the velocities of only some points along the vertical direction in the centre of the cylinders can be measured in this study. The measurements were taken at eight or nine locations, which were evenly distributed along the vertical direction. In this study, the high-frequency end of the spectral analysis of velocity data measured by the ADV was simply used to estimate the critical angular velocity of the inner cylinder at which the flow in the Couette flow system became a turbulent flow (Hinze 1975). This value was 27 rpm in this experiment, so the sequential order of angular velocity of the inner cylinder of 60, 90, 120 and 180 rpm was used to generate different turbulent flow conditions in this study.

The turbulent fluctuating velocity was used to characterize the shear conditions of the Couette system, as follows. First, the radial, tangential and vertical turbulent fluctuating velocity components ($u'_1$, $u'_2$, $u'_3$) at a measured point $I$ were calculated using the measured velocity data obtained by the ADV. Second, the turbulent fluctuating velocity $u_I$ at point $I$ can be calculated using the following expression (Hinze 1975): $u_I = \sqrt{(u'_1^2 + u'_2^2 + u'_3^2)/3}$. Finally, the turbulent fluctuating values for all measured points were averaged to obtain a characteristic turbulent fluctuating velocity $\tau$, which can characterize the flow shear condition in this study: $\tau = \sqrt{\sum_{I=1}^{N} u'_I^2}/N$. Here, $N = 8–9$ is the number of
locations where the ADV measurement was performed as introduced.

The results indicate that the vertical distribution of the turbulent fluctuating velocity was approximately uniform over the vertical direction of the flow system. This method provides an approximate and simple estimation for the characteristic turbulent fluctuating velocity, and it was used only as a simple basis to compare the effects of different turbulent flow environments on flocculation in this study. The characteristic turbulent fluctuating velocity values $\tau$ corresponding to all angular velocities of the inner cylinder $\omega$ of 60, 90, 120 and 180 rpm were 39.10, 57.60, 70.80 and 103.20 mm/s, respectively. 

**Sediment**

Similar to some reported experiments (Maggi et al. 2007), kaolinite (China clay) was used as the sediment material for the experiment because of its distinct flocculation characteristics. The particle size distribution of kaolinite was measured using a laser particle size analyser (Horiba LA-920; produced by Horiba Corporation, Japan). The median size of the primary particle was 5.07 $\mu$m, with a size range of 0.59–23 $\mu$m.

**Experimental procedure**

A schematic view of the experimental procedure is shown in Figure 1(a). Approximately 556 L of deionized water was poured into the region between the cylinders for each experiment run to ensure that the height of the water-sediment mixture remained at approximately 400 mm during experiments. First, a specific amount of kaolinite with a concentration by volume (the volume of kaolinite divided by the volume of the water–sediment suspension) of $7.87 \times 10^{-5}$ was introduced into the Couette flow system. Then, the annular

![Figure 1](https://iwaponline.com/wst/article-pdf/77/4/861/494154/wst077040861.pdf)
velocity of the inner cylinder was increased to the maximum value for 5 min to guarantee that the kaolinite could be adequately suspended in the system. Compressed nitrogen (N₂) was further released into the water-sediment mixture from a circular hole with a 40-mm diameter at the bottom of the outer cylinder to yield a strong impulse to disperse the suspension so that no new flocs of primary particles might be present before the experiment began.

At the beginning of the experimental run, the specified flow shear condition was rapidly attained by setting the angular velocity of the inner cylinder. Using a glass-made transfer pipette with a 5-mm diameter, a water-sediment sample with an approximate volume of 1 mL was taken from a middle point in the centre of the gap between the outer and inner cylinders. By manipulating the transfer pipette, a sample of 0.1 mL (approximately 2 drops of the sample) was only allowed to fall from the pipette into a small glass volumetric flask (already filled with 1 mL of deionized water) to dilute by self weight. This dilution process was necessary to guarantee that there were no overly crowded flocs in each final sample.

After the dilution process was completed, a dropper with a glass head and another rubber end was used to slightly draw the diluted sample of 0.1 mL (almost 2 drops of the sample) in the flask and carefully return it into the circular concave trough of a slide glass coupled with a cover glass as the final sample for the microscopic observation.

A biological fluorescence microscope connected to a high-resolution charge-coupled device (CCD) (Olympus DP 71; produced by Olympus Corporation, Japan) was used to take photographs of the sample. The camera system consisted of a 1,360 × 1,024 pixel progressive scan and a 2/3-inch colourful CCD camera fitted with a ×4 primary magnification objective lens. The images could be collected at 15 frames per second using the system. The ratio of the pixel to physical length of the collected image was 1 pixel = 1.25 μm, and the minimum detectable particle size was simply set to be 1 × 1 pixel area. Figure 1(b) shows a representative example image of some flocs, which formed at \( \tau = 70.80 \text{ mm/s} \) with the flocculation time of 55 min.

After all images were saved on a personal computer, the projected area \( A \), perimeter \( P \), and length \( L \) of the longest axis of all flocs in a projected two-dimensional plane in each image were calculated in this study using the Matlab software (Matlab version 7.0.0.19920(R14), produced by MathWorks Corporation, USA) after image processing. The following expression was used to calculate the equivalent spherical size \( d \) of all flocs: \( d = \sqrt{4A/\pi} \). The floc size distribution and median floc size were estimated based on the statistics of \( d \) for all flocs. For every flow shear condition, at least 500 flocs were considered in the statistics to determine the floc parameter. Two fractal dimensions were calculated from the slopes of the regression lines of relevant parameters in log-log plots based on Equations (1) and (2). Standard errors were applied to determine these fractal dimension values.

In this study, the time intervals at which the samples were taken were experimentally determined from the temporal variation of the median floc size distribution between two sequential recordings, and the sampling operation was stopped when the median floc size reached a steady state. The sampling times were \{0, 10, 20, 60, 80, 120, 160\} min for \( \tau = 39.10 \text{ mm/s} \), \{0, 10, 20, 40, 60, 70\} min for \( \tau = 57.60 \text{ mm/s} \), \{0, 5, 15, 25, 35, 55, 65\} min for \( \tau = 70.80 \text{ mm/s} \), and \{0, 5, 10, 15, 20, 30, 35\} min for \( \tau = 103.20 \text{ mm/s} \). The experimental temperature was set to remain at \( 20 \pm 0.5 \text{ °C} \). More details regarding the experiment can be found in Zhu et al. (2016).

RESULTS AND DISCUSSION

The calculated values of \( D_2 \) for four different characteristic turbulent fluctuating velocities of 39.10 mm/s, 57.60 mm/s, 70.80 mm/s and 103.20 mm/s with flocculation time \( t \) during flocculation are presented in Figure 2(a)–(d). \( D_2 \) was calculated from the slope of the regression line of \( A \) and \( L \) in the log-log plot for all flocs based on Equation (1). The correlation coefficients \( R^2 \) for all regression lines were 0.89–0.95, which indicate a good relationship between log \( A \) and log \( L \).

\[ D_2 \text{ varied between } 1.70 \pm 0.03 \text{ and } 1.89 \pm 0.02, \text{ which is a similar range to those reported by Gorkzyca & Ganczarzcyk (1996). The lower limit of this range is larger than the values in some previous studies (Serra & Casamitjana 1998; Chakraborti et al. 2003; Stone & Krishnappan 2003; Bubakova et al. 2013).} \]

When the flocculation experiment begins, for \( \tau = 39.10 \text{ mm/s} \) (Figure 2(a)), \( D_2 \) first decreases with flocculation time (0 min < \( t < 20 \text{ min} \)) because the flow shear increases the collision frequency among the primary particles according to the Smoluchowski equation (1917), which yields large, highly branched and loosely bound flocs. Beginning at 20 min, no variation for \( D_2 \) can be temporarily found (20 min < \( t < 60 \text{ min} \)) possibly because of a balance between floc growth, which results from the flow shear, and the breakages and/or restructurings (structural re-arrangement).
of fragile flocs when they are subject to the flow shear environment. Floc breakage occurs when some primary particles and/or small flocs on the border of a highly branched floc separate from the main floc body when they are exposed to the flow shear, consequently making the floc more compact. Floc restructuring (i.e. a denser adjustment of the floc structure) results in a floc with a larger fractal dimension \( D_2 \). Finally, \( D_2 \) reaches a stable state (i.e. \( D_2 \) no longer changes with time) (80 min < \( t \) < 160 min), which may result from a final dynamic equilibrium among three sub-processes of floculation: floc aggregation, floc breakage, and floc restructuring.

The \( D_2 \) fractal dimension experiences a stepwise decrease during the transition from the initial value (2) to the final steady-state value. This phenomenon is also observed in the following cases.

For \( \bar{u} = 70.80 \) mm/s (Figure 2(c)), \( D_2 \) experiences a stepwise decrease from 5 min < \( t \) < 35 min (if the case of \( t = 15 \) min is simply considered an outlier) before reaching an approximate steady state (55 min < \( t \) < 65 min) (since \( D_2 \) at \( t = 55 \) min does not significantly deviate from that at \( t = 65 \) min).

A similar progression of \( D_2 \) over \( t \) is found when \( \bar{u} = 103.20 \) mm/s (Figure 2(d)). As the floculation time increases, the \( D_2 \) fractal dimension stepwise decreases from 5 min < \( t \) < 10 min before reaching an approximately steady state at 15 min < \( t \) < 35 min (if the case of \( t = 30 \) min can be simply considered an outlier of the general behaviour here).

The case at \( \bar{u} = 57.60 \) mm/s is slightly different. As shown in Figure 2(b), \( D_2 \) gradually decreases with floculation time until an approximately steady state is reached at \( t > 40 \) min (the three cases of \( t = 40, 60 \) and 70 min can be considered roughly indicative of the attainment of the steady state because there are small differences in \( D_2 \) for these three cases in this study). For this case, no stepwise decrease of \( D_2 \) was observed.

Chakraborti et al. (2003) measured the fractal dimension values of latex flocs at different mixing times during floculation (10, 20, and 30 min) using a non-intrusive optical

![Figure 2](https://iwaponline.com/wst/article-pdf/77/4/861/494154/wst077040861.pdf)
sampling and digital image analysis technique, and they found that the fractal dimension decreased over time in the initial stages of floc formation. This finding is consistent with the experimental result in Figure 2. Chakraborti et al. (2003) inferred that $D_2$ levelled off at longer mixing times (beyond 40 min) (Figure 7 in Chakraborti et al. study), although the authors did not measure the floc properties at these time intervals. The experimental result in Figure 2(b) in this study closely resembles this inference.

Figure 3(a)–(d) show the calculated values of $D_{pf}$ for different characteristic turbulent fluctuating velocities of 39.10 mm/s, 57.60 mm/s, 70.80 mm/s and 103.20 mm/s with floculation time $t$ during floculation. These fractal dimension values were evaluated from the slope of the regression line of $A$ and $P$ on the log-log plot for all flocs based on Equation (2). The correlation coefficients $R^2$ for all regression lines were 0.94–0.97, which implies that there is a strong relationship between log $A$ and log $P$.

$D_{pf}$ ranged from 1.47 ± 0.01 to 1.78 ± 0.02. This range is larger than those reported in previous experiments (Spicer & Pratsinis 1996; Spicer et al. 1996; Serra & Casamitjana 1998; Stone & Krishnapani 2003; Bubakova et al. 2013).

For $\tau = 39.10$ mm/s (Figure 3(a)), $D_{pf}$ initially increases when floculation begins (0 min < $t$ < 20 min), which indicates that some open and irregularly structured flocs are produced since the flow shear increases the collision frequency among the primary particles. When these flocs are subject to flow shear, they experience breakage and/or restructuring. As discussed, floc breakup implies the separation of some primary particles and/or small flocs on the border of the main floc from the main part of the floc structure when the flow shear stress exceeds their binding force. Floc restructuring indicates a denser re-arrangement of the spatial distribution of primary particles in the floc structure. These re-arrangements will smooth out the boundary line of the fractal floc and impede the production of more irregular floc structures, consequently decreasing $D_{pf}$. As a result, the rate at which $D_{pf}$ increases with floculation time decreases (20 min < $t$ < 60 min) despite the floc growth. Finally, $D_{pf}$ attains an approximately steady state at 80 min < $t$ < 180 min, which may result from a final

![Figure 3](https://iwaponline.com/wst/article-pdf/77/4/861/494154/wst077040861.pdf)
balance among the floc aggregation effect, floc breakage effect and floc restructuring effect.

A similar behaviour of $D_{pf}$ with flocculation time is observed for $\bar{u} = 103.20$ mm/s (Figure 3(d)), as follows. A rapid increase in $D_{pf}$ with $t$ occurs at $0 \text{ min} < t < 5 \text{ min}$; then, a slow increase occurs at $5 \text{ min} < t < 15 \text{ min}$. Finally, an approximately steady level of $D_{pf}$ with $t$ is observed at $15 \text{ min} < t < 30 \text{ min}$ (if the case of $t = 35 \text{ min}$ can be simply considered an outlier of the general behaviour in this study).

As shown in Figure 3(c), the case of $\bar{u} = 70.80$ mm/s is different. $D_{pf}$ initially increases with flocculation time ($0 \text{ min} < t < 25 \text{ min}$) to a maximum value at $t = 25 \text{ min}$, as more highly branched flocs are produced because of the fluid shear. Then, $D_{pf}$ decreases with time ($25 \text{ min} < t < 35 \text{ min}$) possibly because of the forceful breakages and restructurings of flocs. Finally, an approximately steady state of $D_{pf}$ is observed at $35 \text{ min} < t < 55 \text{ min}$ (if the case of $t = 65 \text{ min}$ can be considered an outlier here). The increase of $D_{pf}$ between $t = 0 \text{ min}$ and $25 \text{ min}$ has two distinct phases: a rapid increase process ($0 \text{ min} < t < 5 \text{ min}$) and a slow one ($5 \text{ min} < t < 25 \text{ min}$). The latter may be because either the floc breakage or floc structuring begins to play a role in reshaping the floc boundary when the flocculation time is longer than $5 \text{ min}$.

The case of $\bar{u} = 57.60$ mm/s is unique (Figure 3(b)). When the flocculation time increases, $D_{pf}$ increases to its maximum value at $t = 40 \text{ min}$ after a rapid increase at $0 \text{ min} < t < 10 \text{ min}$ and a slow increase at $10 \text{ min} < t < 40 \text{ min}$. Then, $D_{pf}$ decreases with time at $40 \text{ min} < t < 60 \text{ min}$ when the floc breakage and floc restructurings become more pronounced. Although there is a difference in $D_{pf}$ values for $t = 60 \text{ min}$ and $t = 70 \text{ min}$, $D_{pf}$ may continue to be expected to approach an approximately stable level after $t > 60 \text{ min}$, similar to those presented in Figure 3(a), 3(c) and 3(d) in this study.

Spicer & Pratsinis (1996) measured the perimeter-based fractal dimension values of polystyrene flocs in a stirred tank and found that $D_{pf}$ increases from the initial value ($D_{pf} = 1$) to the maximum value of $D_{pf} = 1.29$ when some porous flocs are produced and slightly decreases until a steady state of $D_{pf} = 1.19$ is reached after a long period. The experimental result in Figure 3(c) is somewhat similar to the trend of $D_{pf}$ versus $t$. In addition, Spicer et al. (1996) studied, using image analysis, how the floc structure of polystyrene particles evolved during flocculation induced by the stirring of different impeller configurations, and they presented the following conclusion. Initially, $D_{pf}$ increases with flocculation time (regardless of the impeller type); then, it reaches a steady state when fragmentation becomes significant. For all impellers, the evolution of $D_{pf}$ collapses onto a curve in a constant flow shear condition. There appears to be a strong consistency between this characteristic and the experimental results in Figure 3(a) and 3(d).

This study attempts to plot those time intervals at which two fractal dimensions ($D_2$ and $D_{pf}$) attain their steady state $t_{ss}$ for four flow shear conditions, as shown in Figure 4. A larger characteristic turbulent fluctuating velocity corresponds to faster convergence speeds of $D_2$ and $D_{pf}$ at the steady states; although for $D_2$, the case of $\bar{u} = 70.80$ mm/s no longer supports this conclusion.

This phenomenon can be simply explained as follows. According to the equation in the Smoluchowski model (see also Equations (1), (2), and (6) in Thomas et al. (1999)), the rate of aggregation $\Lambda_{ij}$ between particles/flocs of sizes $i$ and $j$ is proportional to the collision efficiency coefficient $\alpha$ and collision frequency function $\beta_{ij}$ between them and the product of their respective particle concentrations $n_i$ and $n_j$ as follows: $\Lambda_{ij} = \alpha \beta_{ij} n_i n_j$. The coefficient $\alpha$ significantly depends on the effects of all short-range forces between two colliding particles, such as electrostatic repulsion and the van der Waals force. For a given shear-induced flocculation as presented in this study, the coefficients $\alpha, n_i$, and $n_j$ can be simply considered constants. Since the collision frequency function, $\beta_{ij}$, between particles/flocs of sizes $i$ and $j$ is directly proportional to the flow shear rate (Smoluchowski 1917) (see also Equation (6) in Thomas et al. (1999)), a higher flow shear condition leads to more collisions between particles/flocs.
and more rapid floc aggregations according to the abovementioned expression.

Furthermore, the breakage rate function of fragile flocs was expressed as the 1.5 power of the flow shear rate in heuristic models (Winterwerp 1998; Winterwerp et al. 2006; Son & Hsu 2008). Thus, the complete process of floc aggregation, floc breakage and floc restructuring progresses faster in higher flow shear environments. This phenomenon results in an early occurrence of the steady state of the fractal dimensions during flocculation in stronger flow shear conditions.

This study discussed the changes in the structural and morphological properties of flocs during the flocculation process in terms of two-dimensional ($D_2$) and perimeter-based ($D_{pf}$) fractal dimensions, respectively. Furthermore, this study provided a simple physical description of the roles of floc aggregation, floc breakage and floc restructuring in the changes of these fractal dimensions.

Of all fractal dimensions, only the 3D fractal dimension $D_3$ has practical applications in modelling the gravity settling and other hydrodynamic characteristics of flocs (Vahedi & Gorczyca 2011). However, this fractal dimension is very difficult to measure, although some studies used advanced microscopy (Chu & Lee 2004). Furthermore, some studies attempted to propose the indirect calculation of the 3D fractal dimension ($D_3$) of flocs from two-dimensional ($D_2$) and perimeter-based ($D_{pf}$) fractal dimensions (Thill et al. 1998; Maggi & Winterwerp 2004). Thus, after the temporal changes of the two-dimensional and perimeter-based fractal dimensions of flocs during the flocculation process in this study are known, the changes of the 3D fractal dimension of flocs during the flocculation process can be known and further applied to modelling the complete dynamical process of the aggregation, breakage and restructuring behaviours of flocs. As partly mentioned in the introduction part of this paper, some flocculation-modelling studies used a fixed 3D fractal dimension value (Zhang & Li 2003), whereas a variable 3D fractal dimension value was used in other studies (Maggi 2007; Maggi et al. 2007). The calculated temporal change of the 3D fractal dimension of flocs can be incorporated into the present flocculation models to improve the model accuracy via comparison with the measured flocculation process.

CONCLUSIONS

In this preliminary study, a Couette flow experiment was performed to evaluate the temporal variations of the 2D ($D_2$) and perimeter-based fractal dimensions ($D_{pf}$) of kaolinite flocs during flocculation through sampling observation and an image analysis technique. Despite some outliers in the measurement data regarding the fractal dimension values, the experimental results lead to two simple conclusions:

1. The $D_2$ fractal dimension decreases with flocculation time because the flow shear increases the collisions among the primary particles. It may also experience a stepwise decreasing process when the floc breakage and/or restructuring effects become evident before reaching a final approximate steady state, which results from a dynamic equilibrium among floc aggregation, floc breakage and floc restructuring.

2. The $D_{pf}$ fractal dimension rapidly increases with flocculation time (or up to a maximum value) because the flow shear increases the collisions and subsequent adhesions among the primary particles and undergoes a slow increase (or decrease with the flocculation time) when the floc breakage and/or restructuring effects become more pronounced. Finally, an approximate steady state of $D_{pf}$ is attained because of a balance among the floc aggregation effect, floc breakage effect and floc restructuring effect.

Additionally, a stronger flow shear environment makes the steady state of the fractal dimensions occur early during flocculation.

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