Effect of hydrodynamic breakage on floc evolution and turbidity reduction in flocculation and sedimentation processes

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ABSTRACT

Coagulation and sedimentation process is one of the most popular processes in drinking water treatment. Hydrodynamic breakage has a significant impact on the evolution of floc characteristics and the efficiency of turbidity removal. In this work, the effects of hydrodynamic breakage on floc size, fractal dimension, and floc morphology were investigated with an in-situ recognition system. The experiments were conducted in a continuous flocculation and sedimentation reactor equipped with perforated plates to provide different hydrodynamic breakage conditions. The experimental results indicated that the hydrodynamic conditions significantly influenced the floc destabilization and restructuring processes. A low hydrodynamic shear force provided by P1 led to the increase of both bigger sized flocs but accompanied with small particles (0–10 μm). Excessive velocity gradient provided by P3 produced smaller and looser flocs. An appropriate velocity gradient (i.e., the flow velocity through the perforated plate P2 at 18.9 × 10⁻³ m s⁻¹) was conducive for the formation of larger and more compact structures, with higher average floc size and fractal dimension. This flocculation condition in turn resulted in effective improvements in the turbidity removal efficiency. Floc evolution models were described based on the mechanism of the breakage and restructuring process.

Key words: flocculation, flocs, hydrodynamic conditions, sedimentation

HIGHLIGHTS

- Hydrodynamic effects on flocs properties were revealed in a flocculation and sedimentation reactor.
- Evolutions of flocs was recorded by an in-situ recognition system.
- Moderate breakage (G = 69 s⁻¹) promoted the generation of larger flocs.
- Moderate breakage helped to increase the settleability of flocs.

1. INTRODUCTION

Flocculation and sedimentation have been widely used to remove colloids and particles from water as part of the drinking water treatment process (Huang et al. 2016). In the flocculation process, with the addition of flocculants into the suspension, unstable particles form due to the charge neutralization mechanism and aggregate into flocs by adsorption bridging and enmeshment mechanisms (Kim et al. 2001). Subsequently, particles and flocs are removed via solid-liquid separation in the sedimentation process, resulting in the decrease of residual turbidity (Yao et al. 2014; Kang et al. 2016).

Flocculation and sedimentation processes (He et al. 2012). In general, the small particles induced by the breakage of highly porous and loosely connected flocs cannot be effectively removed in the sedimentation process, which negatively impacts the filtration process by shortening the backwash cycle and reducing the filtration efficiency (Alem et al. 2013; Zarchi et al. 2015a; Ren et al. 2016). In contrast, large and dense flocs with low porosity present a high separation efficiency in the sedimentation process, which is beneficial to the subsequent filtration process (He & Nan 2012). Therefore, floc characteristics are important parameters in the flocculation and sedimentation processes.

Flocculation characteristics are highly dependent on hydrodynamic conditions during the flocculation process (Pivokonsky et al. 2011). Both the shear rate of the impeller and the geometry of the flocculation pool could change the flow conditions and further affect the characteristics of flocs (Wang et al. 2018). Rong et al. suggested that a larger variance of floc characteristics

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occurred in the impeller discharge region; that is, the region closer to the impellers (Rong et al. 2013). It has been also reported that a long rapid mix time and high shear rate led to a decrease of the average floc size (Vassileva et al. 2007). In addition, Samaras et al. demonstrated that larger floc growth rates were achieved in the region of low mixing speeds and high residence time (Samaras et al. 2010). He et al. showed that particles gradually grew into bigger flocs under a low shear, whereas the fluid shear could restrict the floc growth and cause floc breakage (He et al. 2012).

In the flocculation process, aggregates experience formation, growth, breakage and regrowth, and then finally achieve a steady state with the balance of floc growth and breakage (He et al. 2012). Therefore, the breakage and regrowth process has been considered as an important process for aggregate restructuring (Moussa et al. 2013). Yu et al. reported that floc breakage caused the rupture of bonds in the aggregates, leading to the changes of floc surface properties (Yu et al. 2011). It has also been suggested that the floc characteristics after breakage depend on the species of aluminum coagulants (Wang et al. 2009). However, most studies on the floc breakage process focus on impeller-induced breakage. To the best of our knowledge, the influence of hydrodynamic breakage on floc evolution and the turbidity removal efficiency has not been reported.

Floc characteristics in flocculation and sedimentation are limited by the small scale of floculators (Saxena et al. 2020; Sun et al. 2020). However, flaky conditions differ from those in actual water utilities (Zhan et al. 2021). There are few concerns on the effect of hydrodynamic conditions on the evolution of floc characteristics in a continuous flocculation and sedimentation process. Our previous studies investigated the temporal evolution of floc properties in a continuous flow device and further obtained an optimal shear rate combination for turbidity removal (Ren et al. 2016; Wang et al. 2016). The effects of hydrodynamic breakage on floc evolution in a continuous flocculation and sedimentation reactor should be taken into consideration.

In addition, floc characteristics were usually obtained and analyzed by the methods of optical microscopy and image analysis (Gorczyca & Klassen 2008; Gorczyca & Ganczarczyk 2010). However, these analysis techniques have to withdraw the floc samples during the sampling procedures, leading to the disruption of the flocs’ structures (Chakraborti et al. 2003; Xiao et al. 2011). In this study, an in-situ recognition system was applied for the non-destructive measurement of floc characteristics (Nan et al. 2015; Yao et al. 2015a). This system can capture the real-time status of floc morphology and eliminate the floc handling issue associated with invasive methods, and it has been successfully applied to monitor and analyze aggregate evolution in previous studies (He & Nan 2012; Ren et al. 2016; Wang et al. 2016).

This study aimed to investigate the effects of hydrodynamic breakage on the evolution of floc characteristics and sedimentation efficiency. In order to obtain an integrated understanding of floc evolution in the continuous flocculation and sedimentation process, a continuous-flow device was applied. A series of flocculation tests were conducted under different hydrodynamic breakage conditions. Floc properties, namely floc average size, fractal dimension and morphology, were obtained and analyzed by an in-situ recognition system. The number of small particles and the effluent turbidity in the sedimentation process were also examined. The mechanisms of floc evolution under different hydrodynamic breakage conditions were also discussed.

### 2. MATERIALS AND METHODS

#### 2.1. Raw water

Kaolin-humic acid stock suspension was prepared according to our previous published study (He et al. 2012). The kaolin stock solution was prepared by dissolving 1.80 g of kaolin (Tianjin, China) into 1 L of tap water at a pH of 12. The kaolin suspension was stirred at 1,000 rpm/min for 60 minutes and kept in the dark for 24 hours. Then, 800 mL of supernatant was collected as the stock kaolin solution. Humic acid stock solution was prepared by dissolving 36 mg of humic acid (Shanghai, China) in 200 mL of 0.1 M NaOH. After being filtered by a 0.45-μm fiber filter membrane, the humic acid was added into the stock kaolin solution. The mixture solution was diluted to 1,000 mL and adjusted to a pH of 7.2. The suspension was stored in the dark and replaced every week. The raw water was prepared by diluting stock kaolin–humic acid suspension with tap water (Harbin, China). Finally, the raw water contained 100 mg/L of kaolin and 2 mg/L of humic acid. A relatively high initial turbidity is required to ensure adequate floc formation and to observe the evolution of floc morphology in the continuous reactor. Several published studies used similar ranges of initial turbidity in flocculation investigation (He et al. 2012; Ren et al. 2016). The characteristics of the experimental water are shown in Table 1.
2.2. Coagulants

Polyaluminum chloride (PACl, Al2Cl(OH)5, Tianjin, China) was selected as the coagulant in this study. The content calculated as Al2O3 was 28%. The stock solution of PACl was prepared by dissolving 10 g of PACl into 1 L of deionized water, which was directly pipetted into the inflow pipe near the inlet of a continual-flow reactor by a metering pump (D25RE2, Dosatron, France). The effects of PACl dosage have been investigated in our previous study (Ren et al. 2016). The most compact flocs and best flocculation efficiency were achieved at the PACl dosage of 3 mg L⁻¹ as Al, which was selected as the optimal dosage and used for all flocculation tests in this study. Similar ranges of PACl dosage have been used in published studies to explore the evolution of flocs in the flocculation and sedimentation (Wang et al. 2018).

2.3. Flocculation and sedimentation procedure

Figure 1(a) shows the schematic of the continual flow flocculation and sedimentation device used in this study. This continuous flow reactor, which was designed with the purpose of simulating actual process in water utilities, has been successfully applied in our previous work (Ren et al. 2016; Wang et al. 2016). The flocculation unit was composed of one rapid mixing pool (pool A) and three flocculation pools (pool B, pool C and pool D). The interior volume of each flocculation pool was 12.5 L (250 mm × 250 mm × 200 mm). Each flocculation pool was equipped with an impeller (R1342, IKA, Germany) to provide the desired velocity gradient (G). The value of G was the mean shear rate provided by the impeller in each pool, as calculated by Equation (1) (Spicer et al. 1996).

\[
G = \left( \frac{\epsilon}{\mu} \right)^{1/2} = \left( \frac{N_p N^3 D^5}{V \mu} \right)^{1/2}
\]  

(1)

where, \( \mu \) is the kinematic viscosity of water and \( \epsilon \) is the average turbulent energy dissipation rate. \( N_p \) is the impeller power number, \( N \) is the impeller speed, \( D \) is the impeller diameter and \( V \) is the stirred tank volume. As coagulant was added, stirring of the suspension was started at \( G = 548 \) s⁻¹ in pool A, which was chosen as the rapid mixing. In pool B, pool C and pool D, the mean shear rate decreased gradually at \( G = 69, 32 \) and \( 15 \) s⁻¹, respectively. The decrease of velocity gradient in pools B, C and D agreed with the actual flocculation utilities. The hydrodynamic condition used in this study are consistent with our previous work (Ren et al. 2016).

Three different perforated plates, denoted as P1, P2 and P3, were selectively installed in the joint of pool B and pool C, as well as the joint of pool C and pool D (shown in the red circle of Figure 1). The length and width of each perforated plate was 200 mm × 250 mm. In each perforated plate, 10 pores of the same area were evenly distributed, with the diameters of 30, 15 and 7.5 mm for the pores of P1, P2 and P3, respectively. As listed in Table 2, five combinations of perforated plates using P1, P2 and P3 were conducted to investigate the effects of hydrodynamic breakage on floc characteristics and sedimentation efficiency. The hydrodynamic shear forces were originated from the installed perforated plate (P1, P2 and P3). Their equivalent shear rates in each pool were calculated as Equation (2).

\[
G_{\text{equivalent}} = \left( \frac{F_0}{\mu V} \right)^{1/2}
\]  

(2)

### Table 1 | Characteristic of experimental water and experimental condition

| Items                  | Parameters | Unit            |
|------------------------|------------|-----------------|
| pH                     | 7.3–7.8    | –               |
| Turbidity              | 100 ± 5    | NTU             |
| Conductivity           | 492        | μS/cm           |
| Total alkalinity       | 108        | mg/L as CaCO₃  |
| Temperature            | 15.0 ± 2   | °C              |
| Inflow rate            | 2.0        | L/min           |
| PACl dosages           | 3.0        | mg/L as Al     |

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where, $F$ is hydrodynamic force, $v$ is the flow velocity via the perforated plate, $\mu$ is the kinematic viscosity of water and $V$ is the volume of the investigated pool.

In the sedimentation process, an up-flow lamella settler was used, which had an interior volume of 81 L and dimensions of 450 mm × 600 mm × 350 mm. The sedimentation tank was divided into three units denoted as unit E, unit F, and unit G. The lamella plate was installed in unit F. The intervals of each lamella plate were 5 mm, with the angle of 60 degrees. The vertical height of the lamella plate was 100 mm. In the continual-flow reactor, flow was directed through the flocculation pools with a flow rate of 2.0 L min$^{-1}$. The hydraulic retention time in the flocculation process was approximately 20 min. Subsequently,
2.4. Floc characteristics

In the flocculation process, an in-situ recognition system with high-speed digital charged coupled device (CCD) cameras (SVS-VISTEK GmbH, Germany) was applied to capture images of the flocs. The schematic of the in-situ recognition system and the CCD camera configuration is presented in Figure 1(b) (Ren et al. 2016). The pixels of the CCD camera were 992 (horizontal) × 510 (vertical), with the interrogation window of 4,500 μm × 2,310 μm. Nine sites were selected as the CCD camera locations in each flocculation pool (Figure 1(c)). After steady-state was achieved in the reactor after approximately 2 hours, 30 real-time digital images were taken from each CCD camera location to analyze floc characteristics.

Additionally, two online particle counters (2200PCX, HACH, USA) were installed in flocculation pool D and sedimentation unit G in order to record the number of particles smaller than 10 μm. In addition, the effluent turbidity was monitored by an online turbidimeter (100AW, WTW, Germany).

Since flocs have irregular shapes, floc size ($D_p$) can be expressed by an equivalent diameter, as described in Equation (3) (He et al. 2012).

$$D_p = \left(\frac{4A}{\pi}\right)^{1/2}$$

where $A$ is the projected area of a floc. The average floc size was the average value of the floc sizes calculated from 30 images obtained by the CCD camera device.

The two-dimensional projection boundary fractal dimension ($D_f$) was an important parameter to depict the surface morphology of the flocs (Niemeyer et al. 1984). $D_f$ is a statistical quantity to represent the extent of fill space in the fractal flocs (He et al. 2012). $D_f$ could reduce the interference of self-similar and scale-invariant aggregates, as calculated by Equation (4) (Johnson et al. 1996).

$$A \propto P^{D_f}$$

where $P$ is the particle perimeter, and $A$ is the particle projected surface. Both $P$ and $A$ were obtained by analysis of flocs images. The value of $D_f$ shifting from 1 to 2 suggests that the aggregate’s projected area converts from a linear structure to a circular structure (Yao et al. 2015b).

3. RESULT AND DISCUSSION

3.1. Effect of hydrodynamic breakage on floc characteristics

3.1.1. Effect of hydrodynamic breakage on floc size and fractal dimension

Hydrodynamic breakage presents obvious influences both on the evolution of floc size and fractal dimension in the continuous flocculation process. Note that there is no visible sediment during flocculation. As shown in Figure 2(a), the general trend of floc growth was broadly similar in all experimental groups with coagulation dosage of 3 mg L$^{-1}$ as Al. The average size of flocs was around 40 μm in pool B and presented gradual increase trends in pool C and pool D under different hydrodynamic
breakage conditions. While Figure 2(b) suggested that the change of floc fractal dimension in continuous flocculation process did not have obvious law with different hydrodynamic shear forces, which was not consistent with the variation of floc average size.

For P1-P1 group, the average size of flocs in pool D slightly increased to 73 μm, compared with 69 μm for the blank group (P0-P0). Meanwhile, the values of fractal dimension in pool B, C and D for P1-P1 group were also similar to those for blank group. This implies that insufficient hydrodynamic breakage presented limited effects on floc regrowth, which has been found in a previous study (Torres et al. 1991).

For P2-P2 group, the average size of floc evolved to a larger size in pool C, and then reached the largest steady-state size of 84 μm in pool D. Simultaneously, the floc fractal dimension in pool D (1.84 in the P2-P2 group) was higher than that without breakage (1.74 in the blank group). It seems that the hydrodynamic shear force provided by P2-P2 perforated plate combination promoted the breakage and regrowth of flocs, which allowed more small particles contacting with broken bonds in broken flocs to regrow large flocs with more compact structure.

For P3-P3 group, both the average size and fractal dimension of the flocs in pool D were remarkably lower than those in blank group. This could be attributed to the fact that a dramatic increase in flow rate notably introduced strong hydrodynamic shear force with higher breakage intensity. Then, increasing frequency of particle collisions induced by higher hydrodynamic shear force would restrict the regrowth process of broken flocs, leading to the reformation of small and elongated flocs. This phenomenon has also been found by other researchers in flocculation jar-test (Serra et al. 2008).

3.1.2. Effect of hydrodynamic breakage on floc size distribution

Figure 3 illustrates the cumulative number fraction of floc size under different hydrodynamic breakage conditions. It can be observed from Figure 3(a) that the cumulative number of small flocs (<20 μm) gradually decreased and the cumulative number of large flocs (>200 μm) increased in the blank group. The flocs shifted toward larger size, indicating continuous floc growth during the flocculation process without breakage. This result was consistent with the results in Figure 2.

Figure 3(b) shows that, after hydrodynamic breakage by the P1-P1 group, the cumulative numbers of flocs larger than 200 μm and smaller than 20 μm presented an increasing trend. This revealed a fact that some small aggregates were removed from the surfaces of loose flocs in the floc breakage stage, and some intermediate sized aggregates seemed to restructure to bigger flocs (Becker et al. 2009). With the increase of hydrodynamic breakage shear force, the distribution of floc size was shifted toward larger sizes for P2-P2 group (Figure 3(d)). Since the hydrodynamic breakage for the P2-P2 group was obviously higher than that for the P1-P1 group. The flocs in pool B would suffer more serious breakage for the P2-P2 group compared with the P1-P1 group. Therefore, more small particles would be detached from the flocs generated in pool B. According to the results that the proportion of larger flocs notably increased in pool C and D. It could be recognized that the broken flocs would be filled up by small particles and formed larger and more compact flocs in pool C and D.

With further increase of hydrodynamic shear force for the P3-P3 group, the cumulative number fraction of flocs larger than 200 μm decreased obviously and that of flocs smaller than 20 μm apparently increased in pools C and D (Figure 3(f)). This
was remarkably inconsistent with the results under the P₁-P₁ group and P₂-P₂ group conditions. This indicates that further increase of hydrodynamic shear force presents an adverse influence on the re-growth process of broken flocs.

3.1.3. Effect of hydrodynamic breakage on floc morphology

In order to directly observe the floc morphology at the end of the flocculation stage, some representative flocs images under different plate combinations were captured in pool D by the in-situ recognition system, as shown in Figure 4. Compared with the blank group, the number of smaller particles and larger flocs was greater in the P₁-P₁ group. In the P₂-P₂ group, the relatively higher hydrodynamic shear rate produced relatively uniform and larger flocs than the blank group (Figure 4(c)). In general, appropriate breakage could promote the regrowth of flocs (Yao et al. 2015a). However, it can be seen from Figure 4(d) that the flocs formed in the P₃-P₃ group were obviously smaller than in blank group, suggesting excessive breakage restricted the regrowth process of flocs, which was consistent with the results discussed in sections 3.1.1 and 3.1.2. Therefore,

Figure 3 | Flocs size distribution in flocculation pools at different hydrodynamic breakage conditions.
flocs morphology under different hydrodynamic shear force conditions would give some direct observation on the evolution process of flocs.

3.2. Effect of hydrodynamic breakage on effluent quality

3.2.1. Effect of hydrodynamic breakage on effluent particles

Small particles (0–10 μm) are difficult to remove in the sedimentation process, which is expected to have a major negative effect on the following filtration process (Zarchi et al. 2013b). Therefore, the effective removal of small particles by hydrodynamic breakage in the flocculation process was of great significance. As shown in Figure 5(a), the equivalent diameter of particles in the range of 5–10 μm (around 9,000/mL) were apparently higher than the particle sizes less than 5 μm (around 6,000/mL) in all cases. Compared with P0-P0, the hydrodynamic shear force in the P1-P1 group led to a slight increase in the number of small particles. This verified that low intensity breakage in the P1-P1 group aroused the separation of small particles from parent flocs by surface erosion. Besides, inadequate hydrodynamic shear force restricted the collision and re-aggregation between small particles and broken flocs during the flocc regrowth process (He et al. 2012). It was noteworthy that the total amount of small particles in the P2-P2 group was 14,000/mL, which was obviously lower than the amount in the blank group of 15,000/mL. The effective reduction of small particles in the P2-P2 group implied that more small particles were incorporated in the broken flocs during the regrowth process. This was in accordance with the results in Section 3.1 that appropriate hydrodynamic shear force provided by P2-P2 was benefited to the formation of large flocs with more regular shape. In the P3-P3 group, it was interesting to find that the number of small particles was higher compared to the blank group. It also supported the concept that most small flocs were formed during the high intensity breakage period and failed to re-aggregate in the limit regrowth period, which had been found in previous jar test (Yao et al. 2015a). Therefore, it could be concluded that adequate hydrodynamic breakage was prone to reduce small particle amount effectively during the flocculation process.

Figure 5(b) shows the number of small particles in the effluent of sedimentation tank (unit G). It could be found that the proportion of small particles lower than 5 μm was obviously higher than that in the range of 5–10 μm for all the cases, which was just opposite to the results at the end of flocculation process. This suggested that the sedimentation process worked well...
for the removal of small particles in the range of 5–10 μm, but presented poor efficiency for the removal of small particles lower than 5 μm. Similar to the results obtained in the flocculation process, the reduction of small particles in sedimentation tank effluent was also optimal under the role of the P2-P2 group. Furthermore, the total number of small particles in the P3-P2 and P3-P3 groups were notably higher than that in the blank group, implying that excessive hydrodynamic breakage even brings in some negative effects on small particle control. According to previous studies, the amount of particles smaller than 5 μm should be strictly controlled due to their complicated behaviors (Yao et al. 2014). Our previous studies have also demonstrated that small particles would intensify membrane fouling (Yao et al. 2015a, 2015b). Therefore, smaller particle control, in particular particles in 0–5 μm, by using hydrodynamic breakage has important advantages for the mitigation of pollution load in the following treatment process, such as filtration and ultrafiltration.

3.2.2. Effect of hydrodynamic breakage on the effluent turbidity

Table 3 illustrates the effluent turbidity after sedimentation in the continuous flow reactor under different hydrodynamic breakage conditions. Compared with the effluent turbidity of 3.21 NTU in blank group, the minimum effluent turbidity was 2.68 NTU in the P2-P2 group, and the maximum turbidity was 5.19 NTU in the P3-P3 group. The proportions of effluent small particles in Figure 5(b) were positively correlated with the effluent turbidity since turbidity was mainly determined by small particles (Yu et al. 2011). Therefore, adequate hydrodynamic breakage and regrowth process (P2-P2 group) which produced larger and more compact flocs due to the incorporation of more small particles into broken flocs (Figures 2 and 3), would contribute to the lowest proportion of small particles (Figure 5) and corresponding minimum residual turbidity. However, excessive hydrodynamic breakage (P3-P3 group) would result in a deterioration of residual turbidity because of more small particles of effluent water induced by the breakage process of flocs in pools C and D.

3.3. Mechanism of floc evolution in hydrodynamic breakage and regrowth process

As discussed above, hydrodynamic breakage has significant influence on the evolution of floc characteristics, small particle proportion and effluent turbidity. The evolution of flocs characteristics during the flocculation process would determine small

Table 3 | Effluent turbidity (tank G) at different hydrodynamic breakage conditions (NTU)

| No. | Blank | P1-P1 | P2-P1 | P2-P2 | P3-P2 | P3-P3 |
|-----|-------|-------|-------|-------|-------|-------|
| Test 1 | 3.53 | 3.26 | 3.03 | 2.52 | 4.00 | 5.17 |
| Test 2 | 2.86 | 3.25 | 2.77 | 2.69 | 4.80 | 5.59 |
| Test 3 | 3.23 | 2.96 | 3.25 | 2.82 | 4.41 | 4.81 |
| Average | 3.21 | 3.16 | 3.02 | 2.68 | 4.40 | 5.19 |
particle proportions at the end of the flocculation process and sedimentation process, and corresponding effluent turbidity. Therefore, the mechanism discussion regarding the evolution of floc characteristics in the flocculation process could reveal the underlying role of hydrodynamic breakage on the flocculation/sedimentation process. Three models were established based on the floc size (40–90 \( \mu m \)) and the number of small-size particles (0–10 \( \mu m \)). In general, there was more significant difference of the large and small particles, suggesting that more small-size flocs dropped off from the large flocs, related to surface erosion.

Figure 6(a) shows the schematic of floc evolution models under a low hydrodynamic shear force (P1). A gentle hydrodynamic shear force aroused single particles or small aggregates dropped off from the branched structure of parent flocs by surface erosion. This kind of hydrodynamic breakage caused the polarization distribution of flocs, leading to the increase of both big aggregates and small particles (as shown in Figure 4(b)). Kolmogorov’s locally isotropic theory states that the sufficient flocculation can be evaluated from the effective energy dissipation rate (\( \varepsilon \)) in a unit volume (Kolmogorov 1991; Watanabe 2017). Based on this theory, most of turbulence energy was consumed by the big flocs formed by P1 breakage. The big flocs are prone to collision and aggregation with each other, forming larger but more branched flocs. Whereas, less turbulence energy resulted in lower frequency of collisions of small particles in re-flocculation. The inadequate re-flocculation of the small particles led to the significant polarization of the floc size distribution.

When a higher intensity hydrodynamic shear force (P2) was applied in flocculation, as presented in Figure 6(b), the hydrodynamic breakage process shifted from surface erosion towards fragmentation. Flocs were more exposed to break up into intermediate sized aggregates, with a spot of small particles. Due to the concentration of the particle size distribution (Figure 3(d)), the small particles tended to collide and adhere with the intermediate sized aggregates through the diffusion-limited aggregation (DLA) model (Chakraborti et al. 2003), producing more compact and larger clusters. Further aggregation occurred among the clusters, resembling the cluster-cluster aggregation (CCA) model (Gmachowski 2008). This process produced flocs with larger average size and more compact structure (as shown in Figure 2), which were conducive to turbidity removal (Table 3). Therefore, appropriate hydrodynamic breakage (i.e., P2-P2, G: 69 s\(^{-1}\)-69 s\(^{-1}\)) could improve the floc structures and enhance sedimentation efficiency.

![Figure 6](http://iwaponline.com/ws/article-pdf/22/2/1409/1008232/ws022021409.pdf)

**Figure 6** | Schematic of floc evolution models in different hydrodynamic breakage conditions: (a) low hydrodynamic shear force, P1; (b) medium hydrodynamic shear force, P2; (c) high hydrodynamic shear force, P3.
Figure 6(c) shows the floc evolution by hydrodynamic breakage with the large hydrodynamic shear force (P3). The highest flow shear force led to large-scale fragmentation, where flocs were more susceptible to breaking into pieces of similar sizes (Vassileva et al. 2007). Because of the thorough breakage, both the average floc size and the fractal dimension decreased, suggesting the formation of smaller and looser flocs (Figure 2(a) and 2(b)). In addition, the floc size distribution also shifted towards smaller sizes (Figure 3(f)). Although the aggregates could restructure via the CCA mode, the regrowth of aggregates was restricted by the limit re-flocculation period. Therefore, the small aggregates accounted for the main proportion of aggregates after the break and regrowth process.

4. CONCLUSIONS
The effects of hydrodynamic breakage on floc characteristics have been studied in a continuous flow reactor under different hydrodynamic shear force combinations. The results obtained that a gentle hydrodynamic breakage (i.e., the flow velocity through the perforated plate P1 at $4.7 \times 10^{-3}$ m s $^{-1}$) resulted in the surface erosion of flocs. The breakage by P1 formed larger but more branched flocs, as well as more small particles, leading to the polarization of the floc size distribution. The inadequate hydrodynamic breakage presented a limiting effect on small particle control and turbidity removal. In addition, we found that the appropriate hydrodynamic breakage (i.e., the flow velocity through the perforated plate P2 at $18.9 \times 10^{-3}$ m s $^{-1}$) followed a fragmentation mechanism. This breakage process produced flocs with larger average size and more compact structure. The floc size distribution shifted towards larger sizes. Whereas, the excessive hydrodynamic breakage (i.e., the flow velocity through the perforated plate P3 at $75.5 \times 10^{-3}$ m s $^{-1}$) had an adverse effect on small particle control and turbidity removal. Because of the large-scale fragmentation of flocs, the floc size distribution shifted towards smaller sizes. Thus, the present results indicate that installing an appropriate perforated plate in the flocculation pool provides a feasible way to achieve breakage-recombination, thereby enhancing the floc strength and settling performance. The ranges of hydraulic shear force obtained in this study give a certain guidance for the design of the perforated plate, which is beneficial to improve actual flocculation in water treatment.

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DATA AVAILABILITY STATEMENT
All relevant data are included in the paper or its Supplementary Information.

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