Investigation of the hydrodynamic behavior of diatom aggregates using particle image velocimetry

Feng Xiao1,2,*, Xiaoyan Li2, Kitming Lam2, Dongsheng Wang1

1. State Key Laboratory of Environmental Aquatic Chemistry, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China
2. Environmental Engineering Research Centre, Department of Civil Engineering, University of Hong Kong, Hong Kong, China

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Abstract
The hydrodynamic behavior of diatom aggregates has a significant influence on the interactions and flocculation kinetics of algae. However, characterization of the hydrodynamics of diatoms and diatom aggregates in water is rather difficult. In this laboratory study, an advanced visualization technique in particle image velocimetry (PIV) was employed to investigate the hydrodynamic properties of settling diatom aggregates. The experiments were conducted in a settling column filled with a suspension of fluorescent polymeric beads as seed tracers. A laser light sheet was generated by the PIV setup to illuminate a thin vertical planar region in the settling column, while the motions of particles were recorded by a high speed charge-coupled device (CCD) camera. This technique was able to capture the trajectories of the tracers when a diatom aggregate settled through the tracer suspension. The PIV results indicated directly the curvilinear feature of the streamlines around diatom aggregates. The rectilinear collision model largely overestimated the collision areas of the settling particles. Algae aggregates appeared to be highly porous and fractal, which allowed streamlines to penetrate into the aggregate interior. The diatom aggregates have a fluid collection efficiency of 10%–40%. The permeable feature of aggregates can significantly enhance the collisions and flocculation between the aggregates and other small particles including algal cells in water.

Key words: diatom aggregate; fluid collection efficiency; fractal; particle image velocimetry

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Introduction
Algal blooms have become one of the most serious water pollution problems in the coastal waters of Hong Kong and mainland China. Algal coagulation, which transforms small cells to larger and faster settling aggregates, has been considered as an important mechanism of algal bloom termination in marine systems (Jackson et al., 1995; Li and Logan, 1995; Jackson and Burd, 1998).

Based on field observations and particle coagulation theories, Jackson (1990) proposed a model combining both algal growth kinetics and particle coagulation to describe the algal flocculation dynamics. A similar modeling approach has been used by Boehm and Grant (1998) for better understanding the physical and biological factors which addressed the algal population dynamics. However, both models were derived from Smoluchowski’s model (also called the rectilinear model) assuming that particles approach each other straightforwardly until collision occurs (O’Melia and Tiller, 1998). Therefore, the algal cell concentrations predicated by the models are much higher than those actually observed in the field (Millgan and Hill, 1998). Apparently, these models overestimated the collision efficiency by ignoring the influences of the hydrodynamic behavior and the structural morphology of aggregates on the interaction and flocculation between suspended particles in water.

Diatom aggregates are highly porous with properties described by fractals (Logan and Kilps, 1995; Li and Logan, 1995; Li et al., 1998). The interior flow through the diatom aggregates caused by the porous-fractal structure has been proven to affect the hydrodynamic behavior significantly, and hence the particle flocculation and biomaterial transport (Li and Logan, 1997; Li et al., 2003). To describe more accurately the flocculation of an algal bloom, Zhang and Li (2003) developed a fractal-curvilinear model to describe the flocculation process based on previous work by Han and Lawler (1992). Many conventional settling column experiments (Li and Logan, 1997) were carried out to find out the inherent relationship between the reduction factor and the permeability of the particles. However, these experiments just predicted the floc permeability from the floc terminal velocity and could not provide detailed information about the hydrodynamics in the creeping flow field. A bubble-tracking technique was utilized to visualize the flow field near the settling floc (Tsou et al., 2002; Wu and Lee, 1998; Wu et al., 2002; Pietsch et al., 2002). However, this technique does not follow the motions of water
molecules induced by the falling particle. It just shows the trajectories of the buoyant bubbles. Thus, the bubble-tracking technique cannot give the exact information of the flow field. Therefore, there is still a lack of direct evidence of the internal flow through particle aggregates. It is desirable to have streamline information for specifying the hydrodynamic features and the internal permeation of diatom aggregates.

With the development of optical techniques, particle image velocimetry (PIV) does provide us an opportunity to examine the curvilinear model. PIV is a non-intrusive method to capture whole velocity fields in flows within a millisecond and to study flow sensitive to small perturbations. These advantages indicate the great potential for PIV use in various flow fields. To date, PIV has not been widely applied to study flow related to water treatment processes. Most studies have only utilized this technology to identify the local velocity gradient during floculation process (Cheng et al., 1997; Coufort et al., 2005; Xiao et al., 2011; Zhong et al., 2011a, 2011b).

The aim of this study is to characterize the hydrodynamic behavior of diatom aggregates by using an advanced flow visualization technique in PIV. The PIV experiments were performed to capture the detailed spatial information surrounding falling diatom aggregates from the motion of seeding particles. Hence, the permeability, fluid collection efficiency and collision frequency function of diatom aggregates could be determined. In addition, the hydrodynamic interactions and the flow patterns were considered under different hydraulic conditions.

1 Materials and methods

1.1 Diatom bloom and flocculation

Diatom blooms were produced in rectangular glass tanks with an effective volume of 6 L (20 cm × 20 cm × 15 cm, L × W × H). The tanks were filled with autoclaved artificial seawater (salinity = 30 ppt). Stock standard f/2 media was added to offer enough nutrients for diatom culturing based on the guidance described by Guillard (1975). Artificial light was set at a cycle of 12 hr light and 12 hr darkness in the incubator operated at room temperature (20–22°C). Slight aeration was used to provide a mixing environment and prevent the diatom mass from sedimentation. *Thalassiosira, Chaetoceros gracilis* (Fig. 1a, b), which are long chain cells, were inoculated into the growth tank. After one week, an algae flocculation bloom could be observed and the structure of the grown diatom aggregates was highly porous as shown by microscopic observation (Fig. 1c).

1.2 Particle image velocimetry (PIV) technique

PIV is a whole-flow-field technique providing instantaneous velocity vector measurements in a cross-section of a flow (Raffel et al., 1998). The use of modern charge-coupled device (CCD) cameras and dedicated computing hardware results in real-time velocity maps. PIV results are similar to computational fluid dynamics, i.e., large eddy simulations, and real-time velocity maps are an invaluable tool for fluid dynamics researchers.

PIV was carried out to investigate the creeping flow field around falling diatom aggregates and capture the whole velocity field within a millisecond, and to study the flow sensitivity to small perturbations. According to the PIV principles, a program written by Matlab (Mathworks Inc., USA) was employed to obtain the conventional parameters provided by PIV, such as particle displacements and corresponding velocity components. In addition, the images were also analyzed by direct observation to outline the moving trajectory of a seeding particle induced by the larger falling object. This was used to set up a fixed set of coordinates through the center of the larger falling object. Then, the positions of relevant seeding particles could be digitized using the software WINDIG, which is by far the most effective software to extract data from graphs in the Windows system. The procedure was repeated on consecutive PIV images selected to acquire more digitized points of the same trace particles. The points of the trace particles on different images display their apparent position displacement caused by the falling object. Finally, the digitized points for the same trace particle were connected, which formed a trajectory curve of the seeding particle relative to the falling object. By repeating the image treatment procedure, a group of trajectories around the falling object could be obtained. The trajectories of the PIV tracers would show the flow field, i.e. streamlines, around the falling object. Figure 2 schematically illustrates the trajectories of the seeding particles, or the streamlines, around and through a falling object.

For a permeable aggregate, its internal permeation may be measured by the fluid collection efficiency (η), which is the ratio of the flow passing through the aggregate to the flow approaching the aggregate (Veerapaneni and Wiesner, 1996). The fluid collection efficiency can be estimated from the streamlines around and through the aggregate, or $\eta = (d_i-d)\eta$, where $d_i$ is the span of the streamlines flowing...
into the aggregate relative to the span of the streamlines \((d)\) approaching it (Fig. 2). In addition, a curvilinear reduction factor may be used to relate the curvilinear collision frequency function, \(\beta_{\text{cur}}\), with the conventional rectilinear collision frequency function, \(\beta_{\text{rec}}\), in \(E_{\text{cur}} = \beta_{\text{cur}}/\beta_{\text{rec}}\). The \(E_{\text{cur}}\) value can be calculated using the curvilinear collision model of Han and Lawler (1992). Using the PIV-based streamlines, \(E_{\text{cur}}\) for a large falling particle or aggregate can be estimated from \(E_{\text{cur}} = (d_i + d_s)^2/(d + d_s)^2\), where \(d_i\) is the diameter of the seeding particles. Since \(d_s\) (ca. 10 \(\mu\)m) is so small compared to \(d_i\) that it can be neglected, it can be regarded that \(E_{\text{cur}} = \eta\). Obviously, \(\eta = 0\) means there are no permeable effects in evaluating hydrodynamics of the interactive aggregates; while \(\eta = 1\) means the aggregates are 100% permeable.

1.3 Settling experiments

Figure 3 schematically describes the experimental setup. In the present work, the settling experiments were conducted in a settling column which is a rectangular glass (Borofloat 33, Schott) column with dimensions \((L \times W \times H)\) of 40 mm \(\times\) 40 mm \(\times\) 500 mm. A laser light sheet, generated by expanding a laser beam with a combination of cylindrical and spherical lenses, illuminated a thin vertical planar flow region (< 0.5 mm). Polyamid seeding particles (PSP, Dantec Dynamic Corp., Denmark) with a diameter of 10 \(\mu\)m were placed in the settling column as tracers to represent the streamlines of the fluid. The cultured diatom aggregate samples taken from the incubator were carefully released in the laser sheet from the top of the column and settled at a terminal velocity of \(U\). The movements of the seeding particles induced by falling aggregates were then captured by a recording device, a high speed CCD camera with a resolution of 1280 \(\times\) 1024 (1200.hs, PCO.imaging). The image was continuously recorded and sent to the workstation for further data processing. The stored images were analyzed in an interrogation box. Autocorrelation of the seeding particle coordinates was then applied within the interrogation box to determine a coherent seeding particle displacement. In addition, the structural features of the diatom aggregates, such as size, shape factor \((4\pi A/C^2); 0 = \text{line}, 1 = \text{circle}\) and sphericity (min diameter/max diameter; 0 = line, 1 = circle), were determined by using a computer-based image analysis system (Scion Image, Frederick, USA).

1.4 Morphological analysis

Diatom aggregates formed by particle flocculation are porous and fractal (Jackson, 1990). It is well known for aggregates that the mass \((m)\) of the aggregate scales with its size \(d\) according to Eq. (1)

\[
m \sim d^{D_f}
\]

(1)

where, \(D_f\) is three dimensional fractal dimension. For an aggregate made up of \(N\) particles each of mass \(m_0\) and volume \(v_0\), the mass of an aggregate is related to the number of particles in the aggregate by \(m = Nm_0\).
Therefore, the porosity ($p$) can be derived in terms of

$$(1 - p) = \frac{Nv_t}{V_a}$$

(2)

where, $V_a$ is the volume of aggregate expressed by $V_a \sim d^3$. And, Eq. (1) can be converted to

$$N \sim d^{D_f}$$

(3)

Combining Eqs. (2) and (3), we can therefore derive the fractal scaling relationship

$$(1 - p) \sim d^{D_f - 3}$$

(4)

According to previous research (Johnson et al., 1996; Gmachowski, 2005; Bache and Gregory, 2010), the settling velocity of the aggregate in the Stokes flow region can be described as follows:

$$U \sim (1 - p)d^2$$

(5)

Therefore, the following fractal scaling relationship can be obtained between settling velocity and aggregate size

$$U \sim d^{D_f - 1}$$

(6)

2 Results

2.1 Visual observation of the creeping flow

The frames in Fig. 4 represent the motions of the three seeding particles induced by the larger falling diatom aggregate denoted as A3 (diameter 1256 μm) from a portion of the graphs. The experimental terminal velocity of the falling diatom aggregate was 2.69 mm/sec, corresponding to a Reynolds number of 3.3.

In Fig. 4a, three seed tracers indicated by arrows 1, 2 and 3 were located beneath the diatom aggregate without movement when far away from the larger aggregate. In Fig. 4b, c, the seeds 1, 2 and 3 were pushed away from the centerline of the falling aggregate when it was approaching them. Subsequently, as Fig. 4d reveals, the tracer 2 was missing and the tracer 3 just permeated the void of the aggregate because of the highly fractal-porous structure of the diatom aggregate, and the tracer 1 just swept over the aggregate surface. As the larger aggregate continuously fell down at its terminal velocity, it can be found that tracers 1 and 3 gradually shifted close to the centerline of the aggregate. Hence, the curvilinear features and creeping flow surrounding the diatom aggregates were directly demonstrated using the PIV technique. It clearly showed that the rectilinear model should overestimate the collision potential. Moreover, it is necessary to account for the porosity and curvilinear effects to modify the existing collision frequency functions and to improve the understanding of algae flocculation.

2.2 Settling velocity and morphology

The settling velocities in water of the investigated diatom aggregates ranged from 1.88 to 5.84 mm/sec (Fig. 5). The corresponding Reynolds numbers were in the range of 1.59–11.79. The settling velocities measured were in general agreement with those reported in previous studies.

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Fig. 4 Trajectories of seeding tracers related to falling diatom aggregates. Frames (a–f) show the position change of the seeding tracers (1–3).
(Li and Yuan, 2002). The slopes of the settling velocity against size after log-log transformation were 0.87 ($r^2 = 0.70$). Therefore, according to the relationship between the free-falling velocity and the size, the diatom aggregates have an average fractal dimension $D_f = 1.87$, indicating the fractal nature of marine aggregates.

### 2.3 Flow pattern

Once the images were captured and stored in the computer, the PIV interrogation program was applied to obtain the raw displacement vector data. In our approach, the interrogation area was 48 pixel $\times$ 48 pixels and the overlapping size was half of the interrogation area so that there were enough particle pairs to provide reasonable data. The signal to noise ratio was employed to calculate the average vector in one interrogation area. In the Fig. 6, typical flow patterns under different conditions are presented. The sizes of the diatom aggregates A1, A2 and A3 were 844, 1940 and 1257 $\mu$m, respectively.

Figure 6 shows the three velocity fields of diatom aggregates A1, A2 and A3 corresponding with Reynolds numbers (Re) of 1.75, 8.48, and 3.25 respectively. It can be noticed that the flow patterns were quite different. The length and the density of the vectors were increased with increasing Re. These results indicated that higher Re would enhance the hydrodynamic interaction between approaching particles. The diatom aggregate A2 was very special. There were some obviously hollow spaces in the middle of the aggregate.

### 2.4 Streamline determination

The positions of the seeding particles in relation to the falling particle can be identified directly from the PIV video image. A streamline around the falling diatom aggregate can then be determined from the trajectory of a tracer. By repeating the procedure, a group of streamlines surrounding the large falling particle can be formulated (Fig. 7). Figure 7 summarizes the positions of the seeding particles and presents the trajectories of the performed experiments. It can be found that the motions of the seeding particles can be classified as three groups. One is open-channel movement. The second is that the seeding tracers will clog in the diatoms, and the last is that some tracers will permeate through the aggregates. All of these three group streamlines showed curvilinear effects and indicated the fractal-porous features of the diatom aggregates. The PIV results provide direct evidence for validation of the curvilinear model that has been used to calculate the curvilinear reduction factor relative to the rectilinear prediction of particle collisions (Han and Lawler, 1992). For diatom aggregates, the curvilinear reduction factors ranged from 0.008 to 0.42 (Fig. 8). However, the curvilinear reduction factors determined from the PIV study were generally three orders of magnitude greater than those predicted by the curvilinear model (Han and Lawler, 1992). From the obtained streamlines, the fluid collection efficiency for A1, A2 and A3 also can be estimated from the dimensionless cross-sectional area $E_{cur} = (d_i + d_s)^2/d_i^2$ as 0.12, 0.42, and 0.20 respectively. That is, 12%, 42% and 20% of the approaching fluid flows through rather than flowing around the investigated diatom aggregates. Clearly, the highly porous diatom aggregate A2 could allow 42% the approaching fluid to flow through rather than around it, and the extent of creeping flow was demonstrated to be higher for A3 (20%) than A1 (12%). Therefore, the role of the creeping flow is significant and cannot be neglected. Figure 8 presents a summary of the characteristics of marine diatom aggregates from the PIV settling experiments.

In Fig. 8, the diameter of the aggregate was plotted against the estimated fluid collection efficiency. From the results, it appears that the intra-flow within the diatom aggregate is not a function of the aggregate size. These results are in good agreement with a previous study (Zhang and Li, 2003).
Fig. 7 Streamlines around falling diatom aggregates. A1: $D = 844 \mu m$, Re = 1.75; A2: $D = 1940 \mu m$, Re = 8.48; A3: $D = 1257 \mu m$, Re = 3.25.

Fig. 8 Fluid collection efficiency of the diatom aggregates in PIV experiments.

3 Discussion

The hydrodynamics of permeable aggregates is of interest in the aggregation process. Theoretical work has been conducted to characterize the permeability and the reduction factors (Brinkman, 1947; Happel, 1958; Dullien, 1992; Alder, 1981; Veerapaneni and Wiesner, 1996; Vanni, 2000). In addition, many conventional column experiments (Li and Ganczarczyk, 1992; Li and Logan, 1997; Li et al., 2003) have been carried out to elucidate the inherent relationship between the reduction factor and the permeability of the particles. However, these experiments only predicted the floc permeability from the floc terminal velocity and other factors and could not provide detailed information about the hydrodynamics in the creeping flow field. Hence, the floc permeability could not be accurately determined. Tsou et al. (2002) employed a bubble-tracking technique to observe the flow field to investigate floc permeability. This technique had the great advantage of being able to observe the fluid flow directly. However, this technique does not follow the motions of water molecules induced by the falling particle. It only showed the trajectories of the buoyant bubbles. In our previous study (Xiao et al., 2007, 2011), an advanced visualization technique PIV was successful in studying the creeping flow by analyzing the movements of tracers related to falling solid spheres and particle aggregates of microspheres. Here, based on this technique, the flow pattern, hydrodynamic profile and streamlines of diatom aggregates were also successfully obtained. This proved that the PIV technique is able to capture the flow field around not only falling solid spheres and particle aggregates but also highly porous diatom aggregates.

Diatom aggregates are of quite low fractal dimensions ($D_f$), ranging from 1.3 to 2.0 (Logan and Wilkinson, 1991; Jackson et al., 1995), compared with $D_f > 2.1$ of common bioaggregates in water and wastewater (Li et al., 1998; Li and Yuan, 2002). Logan and Wilkinson (1991) calculated diatom aggregates with fractal dimension of 1.52 $\pm$ 0.19. The lower the fractal dimension is, the more porous the aggregate is. The curvilinear reduction factors of diatom aggregates ranged from 0.008 to 0.42, which were two or three orders of magnitude greater than predicted by the curvilinear model (Han and Lawler, 1992). This suggests that the available curvilinear model may underestimate the collision potential between particles. Compared with our previous PIV study (Xiao et al., 2007, 2011), the reduction factors of diatom aggregates were more than two orders of magnitude higher than those of similarly-sized solid falling spheres, but close to those of aggregate flocs. It appears that the porous-fractal structure of the aggregates could permit flow through the aggregate interior. This significant internal flow permeation would greatly enhance the flocculation of marine aggregates with other particles as well as material transfer through the aggregates. Although determined with only limited data, the fluid collection efficiency of diatom aggregates seems not to be a function of the size of the aggregates. However, the values of the fluid collection efficiency are quite similar to those of aggregate flocs with similar fractal dimension. Hence, this indicates that the fluid collection efficiency may be associated with the fractal dimension and further research may be needed to identify the relationship between them.

4 Conclusions

Settling experiments were performed in a settling column tank filled with a suspension of polyamide tracing particles. Particle image velocimetry (PIV) was carried out to examine the detailed spatial variations of many seeding particles when a free-falling diatom aggregate passed by. The investigation directly observed the flow field sur-
rounding diatom aggregates and noted the existence of intra-flow through the aggregates. This shows that the PIV technique is capable of studying the flow patterns, hydrodynamics and streamlines of falling marine aggregates. The PIV laboratory results indicate that the rectilinear model largely overestimates the collision areas of the suspended particles. However, the available curvilinear model underestimates the collision potentials by more than two orders of magnitude. The marine aggregates formed by flocculation have a porous-fractal structure. The collision areas of the aggregates are about 10%–40%. The results demonstrate the permeable feature of fractal aggregates, which can enhance the collision kinetics as well as mass transfer through aggregates.

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