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Vertical distribution of motile phytoplankton in density currents

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Abstract. Frequently occurred algal blooms in the tributary areas of Three Gorges Reservoir have been demonstrated to be closely related to the density currents in earlier studies. This paper aims at studying the vertical distribution of motile phytoplankton in density currents. To achieve this objective, particle image velocimetry and planar laser induced fluorescence techniques were used to measure the velocity field and the algal distribution in lock-exchange density currents. The vertical distribution of *Chlamydomonas reinhardtii* cells was gained, which was characterized by a lower concentration region above the interface and a higher concentration region below the interface. Moreover, the mechanism of this vertical concentration profile was discussed. The results are essential to understand the mechanisms of the appearance and disappearance of algal blooms in the Three Gorges Reservoir area.

1. Introduction

The Three Gorges Reservoir (TGR) is one of the largest reservoirs in the world, with a storage capacity of 39.9 billion m³, a surface area of 1.080 km², and a control watershed area of more than 1 million km² [1]. Since June 2003, the backwater areas of the tributaries have suffered from the harmful and periodical algal blooms, particularly in the Xiangxi, Xiaojiang and Daning rivers [2]. The most dominant species are the motile with vesicles or flagella, such as *Peridiniopsis*, *Chlamydomonas*, *Aphanizonmenon*, and *Microcystis* [3].

At present, the mechanisms underlying the appearance and disappearance of the algal blooms in the tributaries are still not very clear. Previous studies indicate that the algal blooms in the tributary areas of TGR are sensitive to the variations in thermal stratification and hydrodynamics [4]. The bidirectional density current is the typical flow regime in the tributaries of TGR [1]. The critical depth model, proposed by Sverdrup [5], was used to explain the appearance and disappearance of algal blooms in the Xiangxi Bay [6], the largest tributary in the lower reaches of TGR.

As is known, the appropriate hydraulic condition will cause the algae to float up to the water surface and then the algae blooms occur [7]. The vertical movement and distribution of phytoplankton are governed by the hydrodynamic condition and the phytoplankton’s behavior [8]. Kessler [9] presented that the swimming direction of algal cells was determined by the balance of gravitational and viscous torques. Pedley and Kessler [10] presented a continuum model to describe the behavior and distribution of motile phytoplankton. Durham et al. [11] pointed out that only when the viscous shear exceeded a critical value would the motile phytoplankton accumulate in a thin layer.

In this study, the particle image velocimetry (PIV) and planar laser induced fluorescence (PLIF)
techniques were used to measure the flow field and the distribution of *C. reinhardtii* in the lock-exchange density currents. Moreover, the relationship between the vertical distribution of phytoplankton and the depth-varying shear were analyzed.

2. Materials and methods

2.1. Experimental technique

The PIV and PLIF techniques were used for measurement. The PIV was used to measure the velocity filed. The PLIF was used to measure the distribution of algae. Figure 1 shows the schematic illustration of the experimental equipment and the PIV-PLIF system. All the windows in the laboratory were covered with black and opaque curtains to create a dark environment. An optical laser lens system (MDL-F-447) was employed to provide the 447-nm laser sheet, with approximately 0.35 cm thick. The particles (0.3 µm) of titanium oxide were used for the PIV measurements. The *C. reinhardtii* (FACHB-265) from Freshwater Algae Culture Collection at the Institute of Hydrobiology was used for the PLIF measurements. Two CCD cameras (Baumer HXC40) were used with a spatial resolution of 2048×2048 px². The PLIF camera was fitted with an optical high pass filter (550 nm) to collect the red fluorescence emitted by algae and to block out the 447 nm blue light.

![Figure 1. Schematic illustration of the experimental system (unit: cm).](image)

2.2. Experimental setup

Density currents are very common in lakes, reservoirs and other water bodies. The lock-exchange is a widely-used laboratory-scale set-up that can create two gravity currents propagating horizontally [12]. Here the gravity currents were created in a perspex tank (the length × width × depth is 500 cm × 10 cm × 25 cm) based on the lock-exchange system shown in figure 1.

The solutions were prepared in two big storage tanks, each with a volume of 144 liters. One was filled with freshwater, and the other was filled with saltwater. The same amount of particles and living Chlamydomonas cells were added in both of the storage tanks and stirred adequately. The algae cell density was about 4×10⁵ per liter in each of the prepared solution. A vertical lock gate was inserted in the middle of the perspex tank to divide the tank into two parts. The left part was filled with the prepared freshwater to a depth of 6.5 cm and the right part with the prepared saltwater to the same depth. The fluids were allowed to settle for several minutes before starting the experiment by opening the lock gate. The PLIF camera was set to single frame mode and the PIV camera to double frame
mode. The two cameras recorded every 3 sec during the experiment for a total of 30 min. A reference coordinate system was obtained by recording images on the plane defined by the light sheet after every experiment. Three experiments were carried out and the salinities of saltwater were 0.3‰, 0.4‰ and 0.5‰, respectively.

2.3. Data analysis
The laser sheet through the water is an inverted trapezoidal with a base of 70 mm and a height of 65 mm. Since the intensity distribution of the laser beam is an M shape after passing through the Powell lenses used in the optical laser lens system, only the 30 mm in the middle had a relatively uniform intensity (higher than 80%). Thus, the area of approximately 30×65 mm² in the middle of the laser sheet was used to analyze the algae distribution. The instantaneous two-dimensional velocity fields and gray value fields were analyzed by the PIV and PLIF processing system, which is developed by Beijing Sinfotek Technology Co., Ltd. The attenuation of laser intensity along the optical path was negligible in the experiments, so the gray value fields can represent the distribution of algae cells. The analyzed area of about 30×65 mm² was divided into 27×57 grids (each grid was 1.107×1.107 mm²) for both the PIV and PILE analyses. The average of 120 images represented the time averaged velocity field (or the algal distribution) for every 6 min, and 20 images for every 1 min.

3. Results and discussion
3.1. Velocity field

Figure 2. Velocity distribution (a: the instantaneous velocity field at t=30 sec; b: the instantaneous velocity field at t=6 min 39 sec; c: the instantaneous velocity field at t=20 min 27 sec; d: the time-dependent evolution of sectional velocity and the shear at the position X=40 mm).
The flow fields and the developing process were similar in all of the three experimental cases, and the velocity fields at different times for case 2 (the salinity of saltwater was 0.4‰) were shown in figure 2. When the lock gate was removed, the difference in the hydrostatic pressure induced the saltwater to flow to the left along the bottom of the tank, while the freshwater flow to the right along the water surface. As shown in figure 2 (a), the freshwater around the saltwater head was pushed to turn up during the traveling of the saltwater head [13]. After the head, it was the body part of the lock-exchange gravity current, and the velocity field was shown in figure 2 (b). The body part showed a typical stratified and bidirectional flow field. The horizontal velocity (u) kept decreasing over time, as shown in figure 2 (c).

Seen from the sectional velocity profiles at the position of X=40 mm (figure 2 (c)), the fluid was stratified into two layers. Above the height of Z=26mm was the freshwater layer with positive horizontal velocities while below the height was the saltwater layer with negative horizontal velocities. Between the two layers was the interface with horizontal velocities changing from negative to positive. The whole sectional velocity profile seemed as a heterochiral S. In term of the time series of the sectional velocity profiles (figure 2 (d)), the height of the saltwater layer was increasing slowly over time, and could reach 26 mm at the end of this experiment. Compared to the freshwater, the saltwater had a relatively less thickness and a higher velocity in the whole experiment. The distribution of the shear was shown in figure 2 (d). The distribution of the shear can be described as a cubic polynomial curve in all the three experiments. The shears decreased as the velocity decreased over time. The range of the time averaged shears was from -0.48 s⁻¹ to 0.29 s⁻¹ for t=0~6 min, and was from -0.07 s⁻¹ to 0.05 s⁻¹ for t=24~30 min.

3.2. Algal vertical distribution
Because the hydrodynamic condition cannot obviously change the algal vertical distribution in a short time, an average of 120 images was used to represent a time-averaged distribution for every 6 min. The algal vertical distribution and its developing process were similar in all the three experimental cases, and the algal distributions at different time for case 1 (the salinity of saltwater was 0.3‰) were shown in figure 3. Before the experiments started, algae cells were basically in a homogeneous distribution in the fluids. Thus, the distribution of gray value for the first 6 minutes was relatively uniform, as shown in figure 3 (a). For the case of stable gravity current with head passing the illuminated area, there was a region with relatively higher gray value around the height of Z=16 mm in the saltwater layer (region H) while another region with relatively lower gray value around the height of Z=28 mm in the freshwater layer (region L). The gray value of region H firstly increased to the peak value and then decreased to the gray level of other regions in saltwater as the experiments develops. Thus, the gray level of the whole saltwater was relatively uniform and the region H disappeared finally, as shown in figure 3 (c). On the contrary, the region L existed through the entire experiments. The upper and bottom boundaries of this region was expanding over time and the height of region L almost increased to 20 mm at the end.

There was also an area with relatively lower gray level around Z=50 mm near the water surface, where the horizontal velocity was relatively low and the fluid field was obviously disturbed by removing the gate. Thus, the algal distribution in the region above Z=50 mm near the water surface was not discussed in this research. The light intensity of the laser sheet was especially high at the bottom of the fluid, and the fluorescence induced by the laser was also very intense. Thus, the algal distribution in the region below Z=5 mm at the bottom was also not discussed here. In conclusion, the vertical distribution of algae was uniform at first and gradually changed into a sharp profile in density currents. The vertical distribution profile was characterized as the relatively low algal concentration region above the interface and the high algal concentration region below the interface. With the shear decreased, the low algal concentration region expanded while the high algal concentration region gradually disappeared.
Figure 3. The time series of algal distribution in case 1 (a–e: algal vertical two-dimensional distribution for every 6 min, f: the time-dependent evolution of algal vertical distribution profile).

Figure 4. Gyrotactic trapping and the time series of gray value of saltwater layer and the determination of $S_c$. 
C. reinhardtii used in the experiments is a typical gyrotactic species [14]. In density currents, the velocity gradients give the cell a viscous torque which makes cells spin. Once the cell deviates from the vertical direction, there will be a gravitational torque trying to rotate the cell back to the vertical direction. When the gravitational torque is larger than the viscous torque, the cell can swim upward generally and the direction is decided by the balance of the two torques. But when the gravitational torque is smaller than the viscous torque, cells will spin and accumulate in the layer [11], as shown in figure 4(a). Thus, there should be a critical viscous shear (Scr), above which the C. reinhardtii cells will spin around.

In our experiments, the hydrodynamic shear was increasing from the bottom of the saltwater layer to the interface. In the lower part of the saltwater layer, the shear was less than the critical shear and the algae cells kept swimming upward and left this region a relatively lower concentration. Then the cells kept on going upward to the region with the viscous torque equaled to the critical shear. In this region, the algae cells were trapped and spinning, thus the phytoplankton concentration in this layer was increasing over time with more and more cells from the lower part were captured here. The layer with viscous shear higher than the critical value acted as a barrier preventing algae cells from moving upward. Thus, most cells could not reach this area and forming a low concentration region here. Upon this layer with shear higher than Scr, the shears were smaller than Scr and cells migrated away and forming the upper boundary of the low concentration region, which moved upward with cells swimming upward. As experiments developed, the position of Scr in saltwater was moving down as the whole shear decreased. Thus, the cells near the bottom boundary could swim up again and the bottom boundary seemed to be moving down.

3.3. Critical shear

The critical shear is an important parameter. Only when the shear of the interface is higher than the critical shear can this algal vertical profile be formed. For the Scr appeared in the saltwater layer, the gray level and the shear were analyzed only for the region below Z=30 mm. As can be seen from figure 4 (b), the highest gray level appeared in the second 6 min. An average of 20 images was used to represent a time-averaged distribution for 1 min during the second 6 min (figure 4 (c)). The highest gray level was determined in the ninth min and the vertical distribution of gray level and shear was shown in figure 4 (a). The critical shear and the highest gray value appeared at the same position. For the three cases in this experiment, the critical shears were 0.15 s⁻¹, 0.15 s⁻¹ and 0.13 s⁻¹, respectively.

4. Conclusion

The PIV-PLIF system was used to measure the velocity filed and the algal distribution profile in the lock-exchange density currents. In the whole experiments, the fluid field was stratified and bidirectional. The vertical distribution of horizontal velocity can be described with a heterochiral S shape. The distributions of shear can be approximately estimated with a cubic polynomial curve. The shear near the interface was the largest. The vertical distribution of algae can be characterized as the relatively low concentration region above the interface and the high concentration region below the interface. As the horizontal velocity and the shear decreased, the region with high algal concentration gradually disappeared while the region with low concentration gradually appeared and increased. In these experiments, the critical shear ranged from 0.13 s⁻¹ to 0.15 s⁻¹.

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