Installation of flow deflectors and wing baffles to reduce dead zone and enhance flashing light effect in an open raceway pond

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ABSTRACT

To reduce the dead zone and enhance the flashing light effect, a novel open raceway pond with flow deflectors and wing baffles was developed. The hydrodynamics and light characteristics in the novel open raceway pond were investigated using computational fluid dynamics. Results showed that, compared with the control pond, pressure loss in the flow channel of the pond with optimized flow deflectors decreased by 14.58%, average fluid velocity increased by 26.89% and dead zone decreased by 60.42%. With wing baffles built into the raceway pond, significant swirling flow was produced. Moreover, the period of average L/D cycle was shortened. In outdoor cultivation of freshwater Chlorella sp., the biomass concentration of Chlorella sp. cultivated in the raceway pond with wing baffles was 30.11% higher than that of the control pond.

1. Introduction

Microalgae has caught more and more attention for their high potential to produce pigment, high-value chemicals and biofuels, to remove heavy metals, nitrogen and phosphorus nutrient from wastewater and flue gas (Borowitzka, 2013; He et al., 2015; Pruvoit et al., 2011; Zhu et al., 2014). Currently, most widely used system for mass microalgal cultivation are open ponds, due to their low construction and operation cost. Nevertheless, open ponds have some serious drawbacks including the high risk of culture contamination, the lack of temperature control, the poor gas/liquid mass transfer and the low final biomass concentration (Carvalho et al., 2006; Posten, 2009).

Several studies have been performed to improve open raceway ponds performance, mainly focusing on ponds design and CO2 utilization efficiency. Chiaramonti et al. (2013) investigated the actual energy consumption in a raceway pond and developed innovative solutions to improve the energy performance. Li et al. (2014) compared the effect of four blades configuration on power consumption in a 2.2 m² raceway pond. Ketheesan and Nirmalakhandan (2012) designed an airlift-driven raceway reactor for microalgal cultivation. Hadiyanto et al. (2013) evaluated the effect of velocity, ratio of channel length to width and culture depth on power consumption, dead zone volume and shear stress. Sompech et al. (2012) investigated the flow field of an open raceway pond with flow deflectors and island design, and found that the proportion of dead zone area decreased from 14.2% to 0%, compared to the control pond. In order to improve the CO2 utilization efficiency in the raceway pond, devices such as sumps and mixing columns have been proposed as a means of increasing the gas/liquid contact time and the efficiency of CO2 absorption (de Godos et al., 2014; Mendoza et al., 2013; Putt et al., 2011). However, when sumps are used, more power for mixing is required. In addition, Pawlowski et al. (2014) improved the CO2 utilization efficiency of flue gas through controlling pH in a raceway reactor.

It has been reported that regular mixing, which make algae cells shuttle between light region near illumination surface and dark
region, is beneficial to improve the efficiency of light utilization and photosynthesis (Janssen et al., 2000; Matthijs et al., 1996). Terry concluded that the photosynthetic efficiency can be improved at light/dark frequency higher than 1 Hz (Terry, 1986). However, the L/D frequency in closed photobioreactors and open pond system is in the medium frequency (0.01–1 Hz) range (Grobbelaar et al., 1996). Xue et al. (2011) found that the growth rate of *Spirulina platensis* increased with increasing L/D frequency in the range of 1 Hz or less with a thin-layer flat plate photobioreactor.

To increase the L/D frequency, many efforts have been made by introducing mixers or baffles into traditional photobioreactors (Degen et al., 2001; Perner-Nochta and Posten, 2007; Ugwu et al., 2002; Wang et al., 2014). Degen et al. (2001) set up baffles into a flat panel airlift photobioreactor and found that the biomass productivity of *Chlorella vulgaris* was 1.7 times higher than that in a randomly mixing bubble column with identical dimensions. Wang et al. (2014) developed a novel flat plate photobioreactor with horizontal baffles and cultivation test showed that the maximum biomass productivity in the novel optimized bioreactor was 1.88 times higher than that in a traditional bioreactor without baffles. Therefore, the introduction of static mixers or baffles is a very efficient way to increase biomass productivity for photobioreactors.

For an open raceway pond with shallow bulk liquid volume, it is difficult to produce significant swirl flow with the introduction of ordinary static mixers or baffles. Therefore, special baffles or mixers should be developed to enhance flashing light effect in open raceway ponds.

In this study, in order to reduce the dead zone and enhance flashing light effect, a novel open raceway pond installed with flow deflectors and wing baffles was developed. The hydrodynamics and light characteristics were investigated using computational fluid dynamics (CFD), and the structural parameters of wing-baffle and flow deflector were optimized. The effectiveness of the wing baffles for outdoor cultivation of *Chlorella* sp. was also experimentally investigated.

### 2. Methods

#### 2.1. Description of the novel open raceway pond

The schematic diagram of the open raceway pond with flow deflectors and wing baffles for simulation is shown in Fig. 1. The raceway pond was 4.85 m long, 0.85 m wide and 0.2 m high. Water depth was kept at 0.1 m. The thickness of the central division wall is 0.05 m. In Fig. 1, *l*, *w*, *s*₁, *s*₂, *s*₃ and *x* represent the length of the wing baffles, the width of the wing baffles, the gap between the wing baffle and pond wall along width-direction, the gap between the two neighbouring wing baffles along width-direction of the pond, the distance between two baffles along fluid flow direction and the angle between the wing baffle and fluid flow direction, respectively. *l*₁ and *l*₂ represent straight section length of the flow deflectors at upstream region and downstream region, respectively. In order to reduce the dead zone fraction in the open raceway pond, six computational examples with different flow deflectors combining the same wing baffles were simulated. The dimensions of the flow deflectors were labeled in Table 1.

#### 2.2. Numerical simulation

The open raceway pond was three-dimensionally meshed using the software ANSYS ICEM CFD 13.0 (64 bit), and the simulation was carried out with ANSYS CFX 13.0 (64 bit). The Eulerian two phase model at steady state was used to simulate the flow in the open raceway pond. The standard *k*–*ε* model, which has been widely used for modeling turbulence, was adopted to describe the turbulent flow behavior in open raceway pond (Huang et al., 2014; Wang et al., 2014; Zhang et al., 2013a,b).

For flow simulation in open raceway pond, sliding mesh technique is mostly adopted (Heiz et al., 2014; Sompech et al., 2012), but it is too time consuming. In this work, to reduce computation load, the paddlewheel section is removed from the computational domain, and the flow were assumed to circulate using inlet and outlet boundary conditions (Hadiyanto et al., 2013). To verify grid independency, three different scale grids (1,652,682, 2,703,746, 3,641,348) were used. Results showed that only a slight difference was observed between the computed values of 2,703,746 cells and 3,641,348 cells. Thus, the medium mesh was used for all the cases.

The no-slip boundary condition was used for bottom and pond wall of the open raceway pond, flow deflectors and wing-baffles. For top surface of the pond, opening boundary condition was performed. The high resolution was used both in the momentum equation discretization and pressure equation. The convergence criterion for all simulations was 1 × 10⁻⁵.

As microalgal cells’ movement in the pond determines the pattern of how they are exposed to the light, and thereby their growth rate. So after the simulation was convergent, the data of particle trajectories were processed by CFX-post. The particle diameter used was 10 µm and density was fixed at 1000 kg/m³ to represent microalgae cell. The maximum particle tracking time was set to 40 s.

#### 2.3. Dead zone calculation

Dead zones typically exist in raceway ponds. Researchers have reported that the velocity in the open pond must be higher than 0.1 m s⁻¹ to keep the algal cells in suspension (Becker, 1994; Weissman et al., 1988). Therefore, the value 0.1 m s⁻¹ was used as the threshold of existence of dead zone (Hadiyanto et al., 2013; Sompech et al., 2012). The dead zone volume fraction was defined as following:

\[
x = \frac{V_{\text{dead}}}{V_{\text{pond}}} \times 100\%
\]

(1)
where $x$ represents dead zone volume fraction, $V_{e=0.1}$ is the fluid volume where velocity being lower than 0.1 m s$^{-1}$, $V_{pond}$ is the total fluid volume in the pond.

### 2.4. Light transfer modeling

Based on one-dimensional light attenuation hypothesis, Cornet model was used to calculate light profile along vertical direction in the raceway pond (Cornet et al., 1992).

$$I = \frac{4x_1}{I_0} \left(1 + \frac{x_1^2}{c} - (1 - x_1)^2 \cdot e^{-x_1}\right)$$  \hspace{1cm} (2)

$$x_1 = \sqrt{\frac{E_a}{E_a + E_l}}$$  \hspace{1cm} (3)

$$x_2 = (E_a + E_l)x_1 \alpha cL$$  \hspace{1cm} (4)

where $I_0$ is the incident light intensity ($\mu$mol m$^{-2}$ s$^{-1}$), $I$ is the local light intensity in the raceway pond ($\mu$mol m$^{-2}$ s$^{-1}$), $c$ is the biomass concentration (g L$^{-1}$), $L$ is the light path (m), $E_a$ is the mass absorption coefficient (m$^2$ g$^{-1}$), and $E_l$ is the mass scattering coefficient (m$^2$ g$^{-1}$). In this work, $I_0 = 1000 \mu$mol m$^{-2}$ s$^{-1}$ and $c = 0.5$ g L$^{-1}$. Meanwhile, $E_a = 0.0014$ m$^2$ g$^{-1}$ and $E_l = 0.9022$ m$^2$ g$^{-1}$ for *Chlorella pyrenoidosa* was used (Huang et al., 2014).

To investigate the light characteristics in the raceway pond, the region where the light intensity was lower than a critical value was defined as the dark zone, and the opposite region was defined as the light zone (Luo and Al-Dahhan, 2004). In this study, the critical light intensity of *C. pyrenoidosa* was assumed to be 96.84 $\mu$mol m$^{-2}$ s$^{-1}$ according to a previous report (Sorokin and Krauss, 1958).

Every L/D cycle of a microalgal cell is defined as (Luo and Al-Dahhan, 2004).

$$t_c = t_l + t_d$$  \hspace{1cm} (5)

where $t_c$ is the time for one L/D cycle, i.e. the time for a cell consecutively passes through the light zone and the dark zone; $t_l$ and $t_d$ represent the duration when the microalgal cell resides in the light and dark zone in a single L/D cycle, respectively.

A microalgal cell undergoes numerous L/D cycles when it moves back and forth between the light and dark zones. Therefore, the average L/D cycle ($T_{av}$) of an individual cell is defined as

$$T_{av} = \frac{\sum t_c}{n}$$  \hspace{1cm} (6)

where $n$ is the number of L/D cycles of a microalgal cell.

To obtain a representative value of the entire population, the average period of L/D cycles of each individual cell was utilized to calculate the average L/D cycles of the entire population, which is expressed by the following equation:

$$T_{av} = \lim_{n \to \infty} \left(\frac{1}{N} \sum_{i=1}^{N} T_{av}^i\right)$$  \hspace{1cm} (7)

where $N$ is the number of the cells.

The L/D cycles of each tracking cell particle were determined by combining the light transfer modeling and the trajectory of microalgal cell (Huang et al., 2014). All of the light regime parameters were processed by MATLAB 7.11.0 (64 bit). And 500 particles were selected to ensure the reliability of statistical data.

### 2.5. Outdoor cultivation experiment

In order to evaluate the actual cultivation results of the raceway pond with wing baffles built in, comparative cultivation experiment of *Chlorella* sp. in baffled raceway pond and control pond were simultaneously carried out under the same conditions. *Chlorella* sp. was obtained from Institute of Hydrobiology, Chinese Academy of Sciences. The nutrition medium was BG11 medium, which contains NaNO$_3$ 1500 mg, K$_2$HPO$_4$ 40 mg, MgSO$_4$7H$_2$O 75 mg, Citric acid 6 mg, Ferric ammonium citrate 6 mg, Na$_2$EDTA 1 mg, CaCl$_2$ 27.2 mg, Na$_2$CO$_3$ 20 mg, H$_2$BO$_3$ 2.86 mg, MnCl$_2$4H$_2$O 1.81 mg, ZnSO$_4$7H$_2$O 0.22 mg, Na$_2$MoO$_4$2H$_2$O 0.39 mg, CuSO$_4$ 5H$_2$O 0.08 mg, CoCl$_2$6H$_2$O 0.04 mg per liter of solution. The length of the raceway pond is 5.3 m, the width and height is 1.0 m and 0.35 m, respectively. The same flow deflectors configuration were installed in baffled raceway pond and control pond with $l_u = 0$ and $l_d = 0.2$ m. The dimension of the wing baffles used in our work was $l = 0.1$ m, $w = 0.1$ m, $s_1 = 0.1$ m, $s_2 = 0.1$ m, $s_3 = 0.3$ m, and $x = \pi/6$. The working volume was $V = 508.5$ L. In each pond, the culture was driven by four flat blades to keep fluid velocity at 0.3 m/s. The ponds were naturally illuminated by solar light energy. The averaged light intensity (the average from 9:00 am to 17:00 pm) was 1000 $\mu$mol m$^{-2}$ s$^{-1}$, which was measured by a photosynthetic active radiation sensor (FGH-1, Photoelectric Instrument Factory of Beijing Normal University, Beijing, P.R. China). CO$_2$ was sparged into the cultures by pH feedback control during microalgae cultivation to keep pH value around 7.8. The culture temperature was kept at 25±2°C by sprinkling the wall of the raceway pond with tap water. Clean water was added into the raceway pond to keep the culture volume constant before collecting samples. Biomass concentration through culture period was measured by using previous method (Zhang et al., 2013b).

### 3. Results and discussion

#### 3.1. Comparison of different flow deflectors

Fig. 2a–f presents the simulated dead zone in the open raceway pond with the same wing baffles but different flow deflectors. The dimension of the wing baffles was $l = 0.1$ m, $w = 0.1$ m, $s_1 = 0.05$ m, $s_2 = 0.1$ m, $s_3 = 0.5$ m and $x = \pi/6$. The fluid inlet velocity was 0.3 m s$^{-1}$. The average fluid velocity, pressure loss and dead zone volume fraction in the raceway ponds with different flow deflectors were shown in Table 1.

As shown in Fig. 2a, dead zone widely existed along the semicircular wall of the pond and at the end of the central division region in the control raceway pond. After installing one layer of flow...
deflectors at each bend (Fig. 2b), the dead zone along the semicircular wall in the open raceway pond was almost eliminated, and the dead zone at the end of the central division region was also greatly reduced. Furthermore, the average fluid velocity increased from 0.305 m s\(^{-1}\) to 0.344 m s\(^{-1}\), and pressure loss decreased from 314.083 Pa to 280.636 Pa. With the installation of two layers of flow deflectors at each bend of the pond, the dead zone at the end of the central division region can be further reduced (Fig. 2c–f). From Fig. 2c–e and Table 1, it can be seen that the longer the straight section of the flow deflectors at downstream region was, the less dead zone and the higher fluid velocity it can be obtained. However, an increase of straight section at upstream region resulted in an increase of the dead zone volume and a decrease of the average fluid velocity. Among the five flow deflector structures used in the pond, the Case (e) was the most efficient where the pressure loss decreased by 14.58%, average fluid velocity increased by 26.89% and dead zone decreased by 60.42% compared with the control pond.

3.2. Hydrodynamic characteristics

Fig. 3a and b showed the flow field of the open raceway ponds with and without wing baffles built in, respectively. It can be seen that significant swirling flow was produced in the open raceway pond with wing baffles built in. However, no swirling flow was found in the control pond. The wing baffles used in this work was similar to airplane wings. When water flows over and under the wing baffles, a pressure difference was created. At the tips of the wing baffles, water flows from the high pressure region below the foil to the low pressure region above the foil, creating a vortex off each tip of the baffle. The width of each wing baffle and the gap between baffles along width direction are equal to the depth of the culture, so that circular vortices created by the wing baffles effectively mix the culture from top to bottom (Laws et al., 1983). Pruvost et al. (2002) investigated the effect of hydrodynamic conditions on a microalgae growth by comparing two different flow conditions with axial and swirling motion in a chamber and found the microalgae cultivated in swirling flow condition grew faster than that in axial flow. Similar results were also reported by Zhang et al. (2013a). The swirl flow produced on \(y-z\) plane in the novel open raceway pond can make microalgal cells shuttle quickly between light region (upper liquid layer) and dark region (nether liquid layer). It is beneficial to increasing the frequency of L/D, so as to improve light efficiency and microalgae growth. This is in agreement with the idea promoting microalgal velocity along light propagation direction (Huang et al., 2014).

Fig. 4a and b depicted twenty examples of particle streamlines with injection position at \(x = 0.01\) m, \(z = 0.05\) m in the raceway ponds with and without wing baffles built in, respectively. It can be seen that all the considered particles almost moved along a horizontal direction (\(x\)) and there was no movement on light path direction (\(z\)) in the control pond. However, with wing baffles built in the raceway pond, particles did regular movement on light path direction.

3.3. Light/dark cycles in the ponds

Fig. 5 showed the probability distribution of L/D cycles of the cells under different conditions. The dimensions of the introduced wing baffle were \(l = 0.1\) m, \(s_1 = 0.1\) m, \(s_2 = 0.05\) m and fluid inlet velocity was 0.3 m s\(^{-1}\). As shown in Fig. 5, the fraction of cells in L/D cycles in the pond with wing baffles built in was 98%,

![Fig. 2. Distribution of dead zone in different raceway ponds.](image)

![Fig. 3. Comparison of velocity field in y-z plane in control and novel raceway pond. (a) Control pond; (b) novel pond.](image)
Fig. 4. Comparison of streamlines in the raceway pond with and without wing baffles. ((a) Without wing baffles; (b) with wing baffles.)

Fig. 5. Probability of light/dark cycles in different raceway ponds. ((g) Control; (h) $a = \pi/6, s_3 = 0.5$ m; (i) $a = \pi/12, s_3 = 0.5$ m; (j) $a = \pi/4, s_3 = 0.5$ m; (k) $a = \pi/6, s_3 = 0.3$ m; (l) $a = \pi/6, s_3 = 0.8$ m.)
(Fig. 5h), while that without wing baffles was only 54%, accompanying with 20% in the dark region (L/D cycle is 0) and 26% in the light region (L/D cycle is 40 s). In addition, the period of average L/D cycle in the pond (g)–(l) were 14.05 s, 7.49 s, 5.49 s, 5.85 s, 7.34 s, 4.42 s, 7.49 s, respectively. Compared with the pond without baffles, the period of average L/D cycle in the novel pond installed with wing baffles was largely shortened. Therefore, the light efficiency and the growth of microalgae could be increased (Huang et al., 2014; Xue et al., 2011). Furthermore, with wing baffles introduced into the raceway pond, the probability distribution was more concentrated compared with that in the pond without wing baffles.

As shown in Fig. 5h–l, with the increasing angle between wing baffle and fluid flow direction, the average L/D cycle in the novel pond first increased and then decreased. With the increasing distance between two adjacent baffles along the fluid flow direction, the average L/D cycle increased. It demonstrated that the less the interval between two adjacent baffles along fluid flow direction was, the shorter the average L/D cycle was and consequently the higher the pressure loss was. Therefore, certain distance between the two baffles along fluid flow direction should be chosen in application.

3.4. Comparative outdoor cultivation of Chlorella sp.

The results of comparative cultivation experiments were shown in Fig. 6. The inoculum concentration of Chlorella sp. was 0.70 g/L. It can be seen that, after eight days’ cultivation, the biomass concentration of Chlorella sp. in baffled raceway pond reached 2.50 g/L, which was 30.11% higher than that of the control pond. In the control pond without wing baffles, due to poor mixing along light path direction, algal cells in the region near the bottom of the pond (dark zone) were under an insufficient light condition. It limited the growth rate of the microalgal, then led to lower biomass production. With wing baffles built into the raceway pond, shuttle of algal cell between light zone and dark zone was created, which benefits the growth rate of the microalgae. Therefore, higher biomass production was achieved. The results indicate that wing baffles can significantly improve algal cell growth rate and biomass production.

4. Conclusions

In this study, a novel open raceway pond with flow deflectors and wing baffles was developed to reduce the dead zone and enhance flashing light effect. The results demonstrated that, with installing optimized flow deflectors in the raceway pond, the area of dead zone decreased by 60.42%. Compared to the control raceway pond, in the raceway pond with built-in wing baffles, significant swirl flow could be produced and the average L/D cycle period was shortened from 14.05 s to 4.42 s. The biomass concentration of Chlorella sp. in the wing-baffled raceway pond was 30.11% higher than that of the control pond.

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References


Fig. 6. Effect of wing baffles on biomass concentration of Chlorella sp. during outdoor cultivation.