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Alternatively permutated conic baffles generate vortex flow field to improve microalgal productivity in a raceway pond

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ABSTRACT

Alternatively permutated conic (APC) baffles were proposed to generate vertical and horizontal vortex flow to intensify mixing and mass transfer in a raceway pond. Both clockwise vortexes were generated before and after conic baffles in the main stream to increase perpendicular velocity by 40.3% and vorticity magnitude by 1.7 times on vertical cross section. Self-rotary flow around conic baffles and vortex flow among conic baffles were generated to increase perpendicular velocity by 80.4% and vorticity magnitude by 4.2 times on horizontal cross section. The bubble generation time and diameter decreased by 25.5% and 38.7%, respectively, while bubble residence time increased by 84.3%. The solution mixing time decreased by 48.1% and mass transfer coefficient increased by 34.0% with optimized relative spacing (ε) and height (ω) of conic baffles. The biomass productivity of *Spirulina* increased by 39.6% under pure CO_2 with APC baffles in a raceway pond.

1. Introduction

The high growth rate of microalgae facilitates their large-scale cultivation (Gerchman et al., 2016; Xue et al., 2013). Microalgae are widely applied in engineering to absorb CO_2 in flue gas from coal-fired power plants (Cheng et al., 2015a; Hreiz et al., 2014). Flue gas from coal chemical plants was purified with desulphurization and denitrogenation to give 99.99% CO_2 (He and Feng, 2012) for improving microalgal cultivation. Raceway ponds are the most common microalgal bioreactors given their cheap and facile operation (Fernández et al., 2016). How to improve microalgal solution mixing with optimized vortex flow is essential to promote biomass growth rate. How to strengthen CO_2 mass transfer with optimized bubble evolution is important to increase CO_2 fixation efficiency for microalgal biomass.

Zhang et al. (2015) developed flow deflectors and wing baffles to enhance the flashing light effect in raceway ponds. Huang et al. (2015) simulated the hydrodynamic characteristics of wing baffles, noting that the average vertical velocity and microalgal biomass productivity increased by 6.8% and 30.1%, respectively. However, these wing baffles did not produce horizontal vortex flow field and increased flow resistance, thus increasing energy consumption. Chiaramonti et al. (2013) installed baffle boards in a raceway pond to reduce the head losses and energy consumption, but the work cannot produce vortex flow field which was beneficial to the growth of microalgae. Huang et al. (2016) and Putt et al. (2011) suggested that excavating a sump at the bottom of the raceway pond promoted bubble generation and evolution. However, the sump caused sedimentation of the microalgae, and poor fluidity in the sump affected the liquid mixing and air-to-liquid mass transfer. Thus, the reported microalgal biomass productivity was low at 10.52 g/(m^2 d).

Cheng et al. (2015b) developed a novel up-down chute baffle that produces clockwise and anticlockwise vortex-flow fields to be applied in raceway ponds. The chute baffle decreased liquid mixing time and increased air-to-liquid mass transfer coefficient. However, it is unsuitable for engineering applications because of its complex structure, high production cost and inconvenient installation. Yang et al. (2016) simulated the fluid vertical velocity of the novel up-down chute baffle which showed the baffle increased vertical velocity by 75% and biomass productivity by 22%. However, they did not describe the distribution of shear stress and vorticity magnitude around the up-down chute baffles, which are crucial to depict the vortex flow characteristics.

Installation of baffles in raceway pond is beneficial to keep the cells in suspension, enhance vertical mixing (Zhang et al., 2015), prevent thermal stratification (Ugwu et al., 2008), and reduce oxygen inhibition (Demirbas, 2010) which helps to improve the microalgal biomass growth rate. Culture temperature strongly affects the microalgal biomass productivity, with the rise of culture temperature, biomass growth rate increases gradually and biomass growth rate of *Spirulina* peaks at around 35 °C (Jiménez et al., 2003). However, baffles in the raceway pond will increase the construction and operation cost to some extent, as the power consumption for flow mixing and the clean for depositional microalgae on baffles will increase in routine operation.

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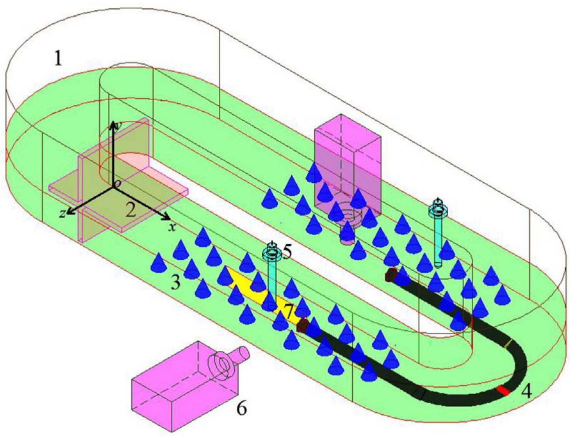
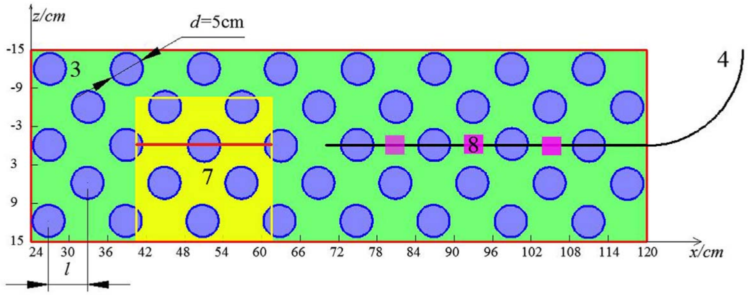


(a) Overview of APC baffles and measurements.



(b) Top view of APC baffles.

Fig. 1. Schematic of alternatively permutated conic (APC) baffles and measurements in a raceway pond. (1. raceway pond, 2. paddlewheel, 3. conic baffles, 4. gas aerator, 5. pH or dissolved oxygen probes, 6. high-speed digital camera, 7. typical zones for computational fluid dynamics, 8. monitoring zones for high-speed digital photography).

Alternatively permutated conic (APC) baffles were originally proposed to generate vertical and horizontal vortex flow to intensify mixing and mass transfer in a raceway pond. The vortex flow field of vertical and horizontal direction was simulated separately with computational fluid dynamic method. Bubble generation properties and residence time were measured with high-speed digital photography. The solution mixing time and mass transfer were measured with online pH/dissolved oxygen electrodes. The relative spacing (ε) and height (ω) of APC baffles were optimized to improve microalgal productivity of *Spirulina* biomass under pure CO_2 in a raceway pond.

2. Materials and methods

2.1. Numerical simulation of a raceway pond modified with APC baffles

As shown in Fig. 1, the raceway pond is 200 cm in length, 60 cm in width, and 35 cm in height. The diameter of the conic baffle is $d = 5$ cm, and its height is $h_1 = 6$ cm. The center of the paddlewheel was set as the origin point of coordinates. The spacing of conic baffles in the x axial direction was set as l and as 6 cm in the z axial direction. Therefore, the global dimension of the raceway pond was x = (−60, 160) cm, y = (−17.5, 17.5) cm, and z = (−65, 15) cm. The ratio of height of conic baffles h_1 to depth of microalgal solution h_2 was defined as relative height ω, that is, $\omega = h_1/h_2$ (as shown in Fig. 5(c)). The ratio of x directional spacing of conic baffles l to diameter of conic baffles d was defined as relative spacing ε, that is, $\varepsilon = l/d$ (as shown in Fig. 5(c)). During the experiment, relative height ω was changed within 0.2–1.0 by adjusting microalgal depth h_2, and relative spacing ε was changed within 1.0–5.0 by adjusting x directional spacing of conic baffles l.

Three-dimensional modeling was conducted with ANSYS ICEM CFD 15.0 (64 bit), and the numerical simulation was performed with ANSYS FLUENT 15.0 (64 bit). The simulation zones were divided into paddlewheel movement zone and fluid steady zone using sliding mesh (Yang et al., 2016). The two zones were connected with cylindrical interface so that two zones could slide past each other. The computational simulation employed the Volume of Fluid (VOF) model and RNG k-ε turbulence model. The transient time step size was set as 0.0002 s, and time step number was set as 15000. Three different grids (950,048; 1405, 298; and 1,832,343 cells) were used to verify grid independency. Only a slight difference was observed. Therefore, the medium grid with 1405, 298 cells was used for all calculation cases. The solution depth was 10 cm, and the paddle wheel rotational speed was 30 rpm. There were two monitoring planes: the horizontal cross section (HCS): x = (40.5, 61.5) cm, y = −15 cm, z = (−7.5, 15) cm and vertical cross section (VCS): x = (40.5, 61.5) cm, y = (−17.5, −11.5) cm, z = 0. The fluid hydrodynamic characteristics in the two cross sections were exported to the software tecplot 360 when the calculation terminated.

2.2. Measurement of bubble generation time and diameter, bubble residence time, mixing time and mass transfer coefficient in a raceway pond with APC baffles

As shown in Fig. 1, a tubular aerator (50 cm in length and 1 cm in diameter) punched with many micropores (1 mm) on surfaces was placed at the bottom of raceway pond. HG-100K colorful CMOS camera was employed for high-speed digital photography. Bubble generation time, bubble generation diameter and bubble residence time were measured using the method introduced by Yang et al. (2016). To maintain the homogeneity of the samples, bubbles were selected at three equidistant positions (as 8 shown in Fig. 1).