



Improving microalgal growth with small bubbles in a raceway pond with swing gas aerators



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HIGHLIGHTS

- A novel swing gas aerator was developed to generate small bubbles in raceway pond.
- A water pump instead of a paddlewheel was used as the impetus source.
- Bubble generation time decreased by 21% when the swing gas aerator was used.
- Improved mass transfer coefficient with baffles increased biomass yield by 18%.

ARTICLE INFO

Article history:

Received 4 April 2016

Received in revised form 18 May 2016

Accepted 19 May 2016

Available online 21 May 2016

Keywords:

Swing gas aerator

Microalgae

Water pump

Raceway pond

ABSTRACT

A novel swing gas aerator was developed to generate small bubbles for improving the mass transfer coefficient and microalgal growth rate in a raceway pond. A high-speed photography system (HSP) was used to measure the bubble diameter and generation time, and online precise dissolved oxygen probes and pH probes were used to measure the mass transfer coefficient and mixing time. Bubble generation time and diameter decreased by 21% and 9%, respectively, when rubber gas aerators were swung in the microalgae solution. When water pump power and gas aeration rate increased in a raceway pond with swing gas aerators and oscillating baffles (SGAOB), bubble generation time and diameter decreased but solution velocity and mass transfer coefficient increased. The mass transfer coefficient increased by 25% and the solution velocity increased by 11% when SGAOB was used, and the microalgal biomass yield increased by 18%.

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1. Introduction

Microalgae have become a research hot spot in CO₂ emission reduction and new energy development (Boruff et al., 2015; Huntley et al., 2015). Raceway reactors are commonly used in microalgal cultivation systems because they are easy to operate and scalable (Harun et al., 2010). Operation costs can be reduced when CO₂ from flue gas of a coal-fired power plant is used (Da Rosa et al., 2011).

An event-based pH control system was developed for microalgae culture in a raceway pond with flue gas (Pawlowski et al., 2014). Application of this control technique accommodates the effective usage of flue gases and helps maintain the optimal growth conditions for microalgae culture. However, the paddlewheel efficiency is only approximately 44–64% (Weissman et al., 1988) even though the raceway pond reactor has the lowest energy cost

compared with other common microalgae reactors. The energy cost of the raceway pond maybe further reduced if the paddle wheel efficiency is improved. The power consumption of four blade configurations was determined in a bench-scale open raceway pond of 2.2 m² (Li et al., 2014). The effects of blade configurations, filling levels, and rotational speeds on shaft power consumption, fluid velocity, and wheel efficiency in an open raceway pond were systematically investigated. The maximum paddle wheel efficiency was 0.5 with flat blades at 11 rpm and a culture depth of 15 cm.

Researchers even attempted to test the non-paddle wheel raceway pond culture system because further improvement of the paddle wheel efficiency is difficult. A paddlewheel-free, airlift-driven raceway reactor was researched by Ketheesan and Nirmalakhandan (2012). In this system, ambient air was sparged at a rate of 2.4 L/min to maintain a culture circulation velocity of 10 cm/s. A maximum volumetric biomass productivity of 0.085 dry g/L/day was achieved at a CO₂-to-air ratio of 1%. The power consumption to maintain typical raceway velocities of 8–14 cm/s was reduced by nearly 80% in the proposed system

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compared with the typical paddlewheel design (Ketheesan and Nirmalakhandan, 2011). However, the mass transfer and mixing efficiency were not studied, although the energy balance was analyzed. Furthermore, microalgae biomass sedimentation may occur with the low-velocity culture solution.

Gas aerators play an important role in the microalgae culture system. Small bubbles indicate a large gas–solution interfacial area and high mass transfer coefficient. Microbubble generation driven by a novel fluidic oscillator was used in a novel airlift loop bioreactor (Zimmerman et al., 2009, 2011). With this type of microbubble generator, the mass transfer and growth rate were also analyzed by Ying et al. (2013). This microbubble generator needs high machining accuracy, and flue gas from a coal-fired power plant contains a high amount of condensate water and dust. The microbubble generator cannot be smoothly used for industrial production because the swing flow field can be damaged by condensate water. Therefore, an easy-to-use, stable, low-energy-consumption gas aerator should be developed to successfully fabricate a new type of gas aerator for industrial production. The effect of liquid horizontal flow on bubble generation at the gas sparger (rubber membrane) in oxidation ditches (wastewater treatment) was studied by Loubiere et al. (2004). During growth, the bubble moved downstream and was flattened as an effect of liquid motion. The effects of orifice orientation and gas–liquid flow pattern on the initial bubble size were reported by Liu et al. (2013). However, the mixing time and mass transfer coefficient with this aerator have not been examined.

In the present study, a novel swing gas aerator was proposed, with a water pump instead of a paddlewheel as the impetus source. The bubble diameter and generation time decreased when the rubber gas aerators were swung in microalgae solution. When the water pump power and gas aeration rate increased in a raceway pond with swing gas aerators and oscillating baffle (SGAOB), the bubble generation time and diameter decreased but the solution velocity and mass transfer coefficient increased. Consequently, the mixing process was effectively accelerated, which improved the mass transfer coefficient and microalgal growth rate in the raceway pond.

2. Experiments

2.1. Bubble generation time and diameter measurement with HSP

The schematic of the swing gas aerator and baffle is shown in S-Fig. 1a. The swing gas aerator was made from a 15 mm long piece of rubber hose, which was 0.5 mm in diameter. A stainless steel gas aerator with the same length and diameter was also fabricated for comparison. When the swing gas aerator was operated inside the culture solution, small bubbles were produced because of the enhanced shear lift force. A sodium lamp was used as a light source, and 2000 images were captured per second. The bubble generation time was obtained from the 2000 continuous images. The bubble volume was determined by the correlation: $V_b = Q_g/f$, where Q_g is the gas flow rate, and f is the average for 10 periods of bubble formation (Lu et al., 2014). To simplify the calculation process, 10 bubbles were uniformly selected for calculating the bubble generation time and diameter. The standard deviations of bubble generation time and diameter were calculated based on three independent measurements.

2.2. Measurement of mass transfer coefficient and mixing time

The schematic of the raceway pond with a pump and SGAOB is shown in S-Fig. 1b. The experimental raceway pond was 35 cm deep, 110 cm long, and 35 cm wide. The raceway pond was divided

into four flow channels with a clapboard along the raceway length; each channel was 8 cm wide. 66.6 L deionized water was used and operated at a depth of 20 cm during the measurement of mass transfer coefficient and mixing time. A water pump was used to mix the deionized water or culture solution during the following test. An oscillating baffle was used to enhance the mass transfer coefficient and decrease the mixing time of the raceway pond. Clean water was used in the raceway pond during the experiment. A total of 24 swing gas aerators were used when the mass transfer coefficient and mixing time were measured.

In aqueous environments, inorganic carbon may exist in several alternative chemical forms, CO_2 (aq), H_2CO_3 , HCO_3^- and CO_3^{2-} , CO_2 concentration in the culture solution, which can't be test with probe directly. However, mass transfer coefficient of O_2 relates directly with mass transfer coefficient of CO_2 (Vega-Estrada et al., 2005). Dissolved oxygen concentration in solution can be directly measured with the dissolved oxygen probes. So O_2 concentration was used to calculate the mass transfer coefficient rather than CO_2 concentration. The overall volumetric mass transfer coefficient, $k_L a_L$, was measured and calculated as described by Mendoza et al. (2013). An oxygen concentration of zero was difficult to achieve in the raceway pond reactor because of the large gas–liquid interface. To simplify measurements, a concentration range of dissolved oxygen (DO) from 3.5 mg/L to 5.5 mg/L was used during calculation. The solution-phase mixing time (mixing time) and average horizontal solution circulation velocity (solution velocity) were defined and calculated as previously described (Cheng et al., 2015b). During the test, the pH of the water was lowered to 3.2 ± 1 by adding hydrochloric acid (35%, w/v). The alkalinity tracer (5 mL of 12 mol/L sodium hydroxide solution) was added. The response to this pulse was measured with pH probes at two positions in the raceway pond. The pH probes (InPro3253i/SG/120; Mettler Toledo) and DO probes (InPro6850i/12/120; Mettler Toledo) were connected to transmitters (i-7017fc; ICP DAS, Taiwan) and data acquisition software (i-7017fc, ICP DAS, Taiwan). Measurements were automatically recorded every 0.1 s. Both probes were simultaneously used. Thus, the standard deviations of the solution horizontal velocity, mass transfer coefficient and mixing time were calculated based on four independent measurements.

2.3. Microalgal cultivation

Chlorella species were mutated by nuclear irradiation and domesticated with high CO_2 concentrations. The domesticated mutant with the highest growth rate under 15% CO_2 concentration was named as *Chlorella mutant PY-ZU1* (Cheng et al., 2013). The microalgal strain *Chlorella mutant PY-ZU1* was cultured with Brostol's solution (also known as soil extract, SE mesium). The side and bottom walls of the raceway pond were covered with black tape to restrict light penetration. Culture solution was operated at a depth of 20 cm during the microalgal cultivation process. The strain was cultured in the raceway pond at 24 °C under continuous illumination of $40,000 \pm 2000$ lux. CO_2 concentration in the flue gas of a coal-fired power plant usually about 15%. Furthermore, microalgal cultivation costs can be reduced when flue gas from power plants is fully consumed (Cheng et al., 2015a). So the culture medium was continuously aerated with 15% CO_2 at a rate of 1413 mL/min (approximately 0.02 vvm). The gas flow rate was controlled and measured by a mass flow meter (SevenstarCS200, China). Microalgal culture were conducted in an artificial greenhouse during this research. Potential sources of pollution were avoid as far as possible for the single factor variable study. So sterile deionized water was added to the raceway pond to maintain a constant culture volume before collecting the microalgal solution samples. A certain damage to the microalgae cells may be caused by the

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