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Improving microalgal growth with reduced diameters of aeration bubbles and enhanced mass transfer of solution in an oscillating flow field

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HIGHLIGHTS

- Bubble generation and mixing efficiency were optimized with oscillating flow field.
- Bubble diameter decreased by 25% in the oscillating gas aerator.
- Mixing time decreased by 32% when the oscillating baffle was used.
- Optimized oscillating flow field increased biomass yield by 19%.

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ABSTRACT

A novel oscillating gas aerator combined with an oscillating baffle was proposed to generate smaller aeration bubbles and enhance solution mass transfer, which can improve microalgal growth in a raceway pond. A high-speed photography system (HSP) was used to measure bubble diameter and generation time, and online precise dissolved oxygen probes and pH probes were used to measure mass-transfer coefficient and mixing time. Bubble diameter and generation time decreased with decreased aeration gas rate, decreased orifice diameter, and increased water velocity in the oscillating gas aerator. The optimized oscillating gas aerator decreased bubble diameter and generation time by 25% and 58%, respectively, compared with a horizontal tubular gas aerator. Using an oscillating gas aerator and an oscillating baffle in a raceway pond increased the solution mass-transfer coefficient by 15% and decreased mixing time by 32%; consequently, microalgal biomass yield increased by 19%.

1. Introduction

Microalgae are used in technologies for CO_2-emission reduction and new-energy development and have thus been extensively investigated (Boruff et al., 2015; Huntley et al., 2015), Microalgal cultivation costs can be reduced when CO_2 was used (Da Rosa et al., 2011). Raceway reactors, as the most successful application microalgae reactors because of their simplicity and scalability, had been widely researched (Rogers et al., 2014).

The influence of various operational and cultural parameters on the optimized storage and utilization of CO_2 in a 10 m^2 open raceway pond had been investigated. Operating at lower pH values or salinities aggravates CO_2 outgassing (Asadollahzadeh et al., 2014). The use of a carbonation column for CO_2 mass transfer into microalgal culture ponds offers enhanced gas-transfer efficiency and meets the CO_2 demand of high-rate algae outdoor ponds. The mass-transfer characteristics of all sections of a 100 m^2 raceway has been evaluated when a sump was used. Mass-transfer coefficients at a gas flow rate of 6 $m^3\,h^{-1}$ were 164.50 h^{-1}, 63.66 h^{-1}, 0.87 h^{-1}, and 0.94 h^{-1} for the paddlewheel, sump, straight and curved channel sections, with associated oxygen transfer rates of 106 $g\,h^{-1}$, 172 $g\,h^{-1}$, 27 $g\,h^{-1}$, and 39 $g\,h^{-1}$, respectively (Mendoza et al., 2013b). However, studies on the effect of bubble diameter on improving mass-transfer coefficient in raceway pond are few. A closed raceway pond has been constructed by covering a normal open raceway pond with a specially designed transparent cover. This cover prevented supplied CO_2 escaping into atmosphere and thus increased the retention time of CO_2, thereby increasing CO_2 fixation efficiency to 95% under intermittent gas sparging (Li et al., 2013). A raceway pond is generally large (Cheng et al., 2015a), so a large part of it was laminar-flow regime. The aeration gas maybe just stay under the flat cover and escape into the atmosphere when the aeration gas

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flows through the flat cover. Thus, this kind of flat cover cannot effectively decrease the mixing time and increase the mass transfer of a raceway pond reactor. An up–down chute baffle has been developed to enhance flashing light in a raceway pond (Cheng et al., 2015b), vertical solution velocity can be increased clearly when the baffle was added into the raceway pond. However, bubble generation process was not studied, also, the number of this kind baffle was limited in one raceway pond because of its high flow resistance. A new kind of baffle should be developed to enhance the mass-transfer coefficient with low flow resistance in the raceway pond.

The impact of liquid horizontal flow on bubble generation at the gas sparger (rubber membrane) in oxidation ditches (wastewater treatment) had been studied by Loubiere et al. (2004). During the growth of bubbles, they move downstream and become flattened by because of the liquid motion. Effects of orifice orientation and gas–liquid flow pattern on initial bubble size have been studied by Liu et al.(2013). Two-phase flow with T-junction microbubble aerators have also been systematically studied (Chen et al., 2015; Peng et al., 2015; Zhang et al., 2015). However, mixing time and mass-transfer coefficient using this kind of aerator have not been examined. Microbubble generation with a novel fluidic oscillator driven has been used in a novel air-left-loop bioreactor (Tesar et al., 2006; Zimmerman et al., 2009; Zimmerman et al., 2011). With this kind of microbubble generator, mass transfer and growth rate have also been analyzed by Ying et al. (2013). This kind of microbubble generator needs high machining accuracy, and flue gas from a coal-fired power plant contains a high amount of condensate water and dust. Thus, the microbubble generator cannot be smoothly used for the industrial production because the oscillating flow field can be damaged by condensate water. Thus, an easy-to-use, stable, low-energy-consumption gas aerator should be developed to successfully fabricate a new gas aerator for industrial production.

In the present study, a novel oscillating gas aerator combined with an oscillating baffle was proposed to generate smaller aeration bubbles and enhance solution mass transfer, thereby improving microalgal growth in a raceway pond. Results showed that bubble diameter and generation time decreased with decreased aeration gas rate, decreased orifice diameter, and increased water velocity in the oscillating gas aerator. Consequently, the mixing process was effectively accelerated, thereby improving the mass-transfer coefficient and microalgal growth rate in the raceway pond.

2. Materials and methods

2.1. Bubble generation time and diameter measurement with HSP

The schematic of the oscillating gas aerator and baffle was shown in Fig. 1a. The square cross section of oscillating gas aerator was 4 mm × 4 mm, in which compressed gas outlet diameter was 0.3 mm. Compressed gas was broken into smaller bubbles because of the enhanced shear lift force when pump solution waggling intensively inside the oscillating gas aerator. Pump solution velocity was accurately determined by weighing method (Yue et al., 2008). Pump solution volume (V_{solution}) from the oscillating gas aerator was collected within a certain time (t), so water velocity (v_{velocity}) inside the aerator was calculated as $v_{\text{velocity}} = V_{\text{solution}}/t/S$, where S was the cross-section of the aerator. A sodium lamp was used as light source, and 2000 images were captured per second. Bubble generation time can be obtained by playing 2000 continuous images. Bubble volume can be obtained by the correlation of $V_b = Q_g/f$, where Q_g was the gas flow rate, and f was the average frequency of ten bubble formation (Lu et al., 2014). The standard deviations of bubble diameter and generation time were calculated based on three independent measurements.

2.2. Measurement of mass-transfer coefficient and mixing time

The schematic of the raceway pond with oscillating gas aerator and baffle was shown in Fig. 1b. The raceway pond was 70 cm long, 20 cm wide, and 9 cm deep with each channel 6 cm wide. A paddlewheel was used to mix the culture medium. Clean water was used and operated at a depth of 6 cm during all the tests. Four oscillating gas aerators were used in parallel in the raceway pond during the tests for mass-transfer coefficient and mixing time. The aeration gas rate through each aerator increased from 11.8 ml min^{-1} to 106.0 ml min^{-1} when the total gas flow rate increased from 0.01 vvm to 0.09 vvm. The efficacies of four oscillating gas aerators in Sections 3.2 and 3.3 were nearly consistent with one aerator in Section 3.1.

The accurate position of the oscillating baffle was shown in Fig. 1a. Together with the gas aerator, a better gas–liquid mixing can be achieved. The overall volumetric mass-transfer coefficient (mass-transfer coefficient), $k_L a_L$, was measured and calculated according to Sierra et al. (2008). Decreasing oxygen concentration to zero in the raceway pond reactor is difficult because of the large gas–liquid interface. To simplify measurement, a concentration range of 3.5–5.5 mg L^{-1} was used during calculation. The solution-phase mixing time (mixing time) and average horizontal solution circulation velocity (solution velocity) were defined and calculated according to Mendoza et al. (2013a). During the test, water pH was lowered to 3.1 ± 1 by adding hydrochloric acid (35%, w/v). The alkalinity tracer (5 mL of 12 mol L^{-1} sodium hydroxide solution) was added, and the response to this pulse was measured with pH probes at two positions in the raceway pond. pH probes (InPro3253i/SG/120 mettler Toledo) and dissolved oxygen 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. Standard deviations of liquid velocity and mass transfer coefficient were calculated based on three 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). The side and bottom walls of the raceway pond were covered with black tape to restrict light penetration.

The strain was cultured in the raceway pond at 24 °C under continuous illumination of 30,000 ± 2000 lux. Culture medium was continuously aerated with 15% CO_2 at a flow rate of 250 mL min^{-1}, which was controlled and measured by a mass flow meter (SevenstarCS200, China). Sterilized deionized water was added into the raceway pond to keep the culture volume constant before collecting microalgal-solution samples. A 10 mL sample of microalgal solution was collected daily at two time points: 9:00 and 21:00. Biomass was separated from the medium by centrifugation at 8000 rpm for 10 min (Beckman Avanti J26-XP, USA). Centrifugation was repeated thrice by adding deionized water to remove residual salt from the microalgal biomass. Dry weight was measured after the biomass was dried at 105 °C to constant weight. All experiments for microalgae culture were conducted in laboratory scale raceway ponds under continuous artificial illumination of 30,000 ± 2000 lux. The standard deviation of biomass dry weight of microalgae culture solution was calculated based on three independent measurements.