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Improving CO_2 fixation with microalgae by bubble breakage in raceway ponds with up–down chute baffles

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HIGHLIGHTS

- Generation and rise of aeration bubbles were optimized with up–down chute baffles.
- Bubble generation time decreased due to enhanced liquid velocity at aerator orifice.
- Bubble residence time increased due to decreased vertical velocity with vortexes.
- Optimized aeration bubbles with chute baffles increased biomass yield by 29%.

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ABSTRACT

The aeration gas was broken into smaller bubbles with enhanced local solution velocity to improve CO_2 fixation with microalgae in raceway ponds with up–down chute baffles. A high-speed photography system and online precise pH probes were used to measure bubble generation and residence times, which were affected by paddlewheel speed, aerator orifice diameter, gas flow rate, and solution depth. Bubble generation time (from gas reaching aerator orifice surface to completely escaping from the aerator) decreased because of the enhanced local solution velocity, whereas bubble residence time increased because of the vortex flow field produced by up–down chute baffles. Bubble generation time decreased by 27% and bubble residence time increased by 27% when paddlewheel speed was 10 r/min with an aeration gas rate of 0.03 vvm. The decreased generation time and increased residence time of aeration bubbles promoted microalgae biomass yield by 29% in optimized flow fields in raceway ponds.

1. Introduction

Microalgal energy, related to CO_2 emission reduction and new energy development, has been extensively investigated because microalgae exhibit a rapid growth rate and high efficiency in utilizing energy from sunlight (Singh and Sharma, 2012). Microalgae biomass production is only economically feasible when considering microalgae not only a source of microalgae energy, but foremost the extracted value-added bio-chemicals and liquid fuels (Šoštarič et al., 2012). The optimization of all of the mentioned processes, including biodiesel production (Klofutar et al., 2010), has to be performed in order to attain feasibility. Detailed reaction kinetics of oil transesterification were studied based on mechanism and reaction scheme of individual triglyceride, diglyceride, monoglyceride, glycerol and fatty acid methyl ester containing different combinations of gadoleic, linoleic, linolenic, oleic, palmitic and stearic acids determined by high-performance liquid chromatography by Likozar and Levec (2014).

The highest specific growth rate of *Spirulina platensis* can be obtained with 40–60% culture solution renewal when the microalgae concentration reaches approximately 0.4 g/L (Radmann et al., 2007). It's indicated that the specific growth rate (μ) of *Nannochloropsis salina* (*N. salina*) was strongly affected by light exposure, with μ values of $0.038 \pm 0.013\ d^{-1}$, $0.093 \pm 0.013\ d^{-1}$, and $0.151 \pm 0.021\ d^{-1}$ for 6-h, 12-h, and 24-h light availability conditions, respectively (Sheets et al., 2014). The effects of paddlewheel speeds on the productivity of microalgae were also evaluated by Moazami et al. (2012). The sustainability of algal biomass as a feedstock for biofuels based on microalgae production in open-air raceway ponds was assessed by Handler et al. (2012). A physics-based computational algae growth model was developed by Gharagozloo et al. (2014). This model can effectively predict algae growth in systems across varying scales, and the causes for reductions in algal productivities can be identified. The CO_2 utilization of flue gas was improved through proper pH control

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in a raceway reactor (Pawlowski et al., 2014). A carbonation sump (1 m depth) in a 100 m^2 raceway reactor was operated and found that 66% of carbon was incorporated into microalgal biomass (de Godos et al., 2014). A model for utilizing industrial off-gas to support microalgae cultivation for biodiesel in raceway pond was developed by Laamanen et al. (2014). In general, many parameters of raceway pond reactor, such as light intensity, energy consumption, and temperature, on microalgal growth and sustainable production have been explored. However, studies have rarely combined the flashing light effect with a gas aeration system to enhance the flashing light effect and increase bubble residence time simultaneously when baffles were added into the raceway pond culture system. Smaller bubbles mean larger gas–solution interfacial area and higher mass transfer coefficient. Thus, the microalgae growth rate can be improved when baffles are added into the raceway pond reactor.

In the field of closed microalgae reactor, baffles were studied to improve the microalgae growth rate and CO_2 fixation efficiency. A newly developed flat panel airlift photobioreactor with a defined circulation path was tested for microalgal culture. Biomass yield increased by 2.5 times because the enhanced flashing light effect and increased bubble residence time (Degen et al., 2001). The research result from the closed microalgae reactor showed the role of the baffles on producing vortex flow field and increasing the gas–solution mass transfer coefficient. An up–down chute baffle was invented to enhance the flashing light effect in a raceway pond (Cheng et al., 2015). The solution mixing time was decreased and the mass transfer coefficient was increased by 41% and 25%, respectively when the baffle was used. Thus, the biomass yield increases by 32.6%. However, the bubble velocity and generation and residence times in the culture solution have not been studied. Bubble generation and residence times, which are affected by paddlewheel speed, aerator orifice diameter, gas flow rate, and solution depth, must be measured.

In this study, a high-speed photography (HSP) system and online precise pH probes were used to measure bubble generation and residence times for optimizing generation and increasing aeration bubble trajectory with up–down chute baffles. Results showed that bubble generation time decreased because of the enhanced local solution velocity, whereas bubble residence time increased because of the vortex flow field produced by up–down chute baffles.

2. Methods

2.1. Bubble diameter and velocity measurement with HSP

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 clapboard along raceway length, and each channel was 8 cm wide. A paddlewheel was used to mix the culture solution. Clean water was used and operated at different solution depths in the raceway pond during the experiment. Each sparger was made from a rubber hose (60 cm length and of 10 mm diameter) with pores placed ~2 mm apart. The schematic of the up–down chute baffles and HSP measurement area is shown in Fig. 1. Green areas A and B represent the chute baffles, whereas the blue area represents their support. The chute baffles A and B were both 75 mm wide and positioned 10 and 70 mm, respectively, above the raceway pond bottom.

The rectangular area encircled with blue lines represents the HSP measurement area. To simplify the calculation process, seven calculation areas (1–7, Fig. 1) were selected for calculating the bubble diameter and velocity. Five bubbles were uniformly selected from each calculation area. Sodium lamp was used as a light source, and 1000 images were captured per second. Scale plates were added into the raceway pond above the gas aerator in the vertical direction. Based on the scale plate, the physical size of a pixel size could be calculated with ArcGIS 9.3 and Microsoft Office Excel. With a time interval of 0.001 s, the average bubble diameter (D), average bubble horizontal velocity (V_x), and average bubble vertical velocity (V_y) could be calculated in one calculation area. The standard deviations of these three parameters were calculated based on three independent measurements.

The bubble generation time at the aerator orifice in the downstream of baffles (bubble generation time, as A_1–A_2 or B_1–B_2 in Fig. 2a) indicated the period from gas reaching aerator orifice surface to completely escaping from the aerator (bubble generation area was with a distance of 6 ± 3 cm in the downstream of the up–down chute baffle). Bubble generation time can be obtained by playing 1000 continuous images. The bubble residence time from the aerator to the solution surface in the downstream of baffles (bubble residence time, as the two rise trajectory described in Fig. 2a) indicated the period from bubble escaping from the aerator to it reaching the solution surface in the downstream of baffles. The distance between two neighbor calculation areas was marked as d_i ($i = 1$–6). The bubbles were assumed to have the same vertical velocity (V_{yi}) within the two neighbor half distances $S = (d_{i-1} + d_{i+1})/2$. So, the time bubbles needed to cross this distance could be calculated as $t_i = (d_{i-1}/2 + d_{i+1}/2)/V_{yi}$ ($i = 1$–6). The bubble residence time from the aerator to the solution surface in the downstream of baffles (bubble residence time) could be calculated as $t = \sum_{i=1}^{7} t_i$.

2.2. Measurement of solution velocity and mixing time

The solution-phase mixing time (mixing time) and average horizontal solution circulation velocity (solution horizontal velocity) were defined and calculated as previously described (Cheng et al., 2015). During the test, the pH of the water was lowered to 3.1–3.2 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 (InPro3253i/SG/120 Mettler Toledo) at two positions in the raceway pond (Fig. 1). Solution horizontal velocity and mixing time with different solution depths in the raceway pond indicated that solution horizontal velocity was calculated with the aforementioned method when the solution depth in the raceway pond was different. Two probes were used simultaneously. Thus, the standard deviations of solution horizontal velocity and mixing time were calculated based on four independent measurements.

2.3. Microalgal cultivation

The microalgal strain *Chlorella* mutant PY-ZU1 was cultured with Brostol's solution (also known as soil extract, SE) and measured with the same method described by Cheng et al. (2013). The strain was cultured in the raceway pond at 24 °C under continuous illumination of 30,000 ± 2000 lux.

3. Results and discussion

3.1. Effects of paddlewheel speeds on generation and residence times of aeration bubbles

Forces, such as inertia, drag, shear lift, gas momentum, surface tension, and buoyancy, exist during orifice bubble formation (Liu et al., 2013). These forces can be divided into detaching and attaching forces, according to their effects on the bubble. Shear lift force plays a major role in taking the bubble away from the aerator