Bioresource Technology 221 (2016) 492–497

Contents lists available at ScienceDirect

Bioresource Technology

journal homepage: www.elsevier.com/locate/biortech

Developing a water-circulating column photobioreactor for microalgal growth with low energy consumption

Zongbo Yang, Jun Cheng *, Weijuan Yang, Junhu Zhou, Kefa Cen

State Key Laboratory of Clean Energy Utilization, Zhejiang University, Hangzhou 310027, China

HIGHLIGHTS

- A water-circulating column photobioreactor (WCC–PBR) was developed in this study.
- Bubble generation time decreased by 60.4% in the WCC–PBR.
- Mixing time decreased by 41.5% with the WCC–PBR.
- Total energy consumption decreased by 21.1% with the WCC–PBR.

ARTICLE INFO

Article history:
Received 2 August 2016
Received in revised form 15 September 2016
Accepted 16 September 2016
Available online 20 September 2016

Keywords:
Microalgae
Column photobioreactor
Bubble
Energy consumption

ABSTRACT

A water-circulating column photobioreactor (WCC–PBR) was developed to decrease bubble generation time and mixing time for growing microalgal biomass at low energy consumption. Bubble generation time was decreased by 60.4% and mixing time was decreased by 41.5% owing to an enhanced solution velocity with a water pump. Bubble residence time was decreased by 31.1% and mass transfer coefficient was decreased by 0.4% owing to a reduced distance between air aerator and solution surface. Microalgal growth rate was decreased by 12.7% from 128.9 mg/L day in an air-lifting column photobioreactor (ALC-PBR) to 112.6 mg/L day in a WCC–PBR because of the decrease in residence time of bubbles and an additional shear of cells in a water pump. However, total energy consumption of a WCC–PBR with an air compressor and a water pump was lower by 21.1% than that of an ALC–PBR with only an air compressor.

1. Introduction

Global warming caused by CO_2 emissions has become a significant concern in both energy and environmental aspects. The biological sequestration of CO_2 by photosynthetic microalgae is an important method of CO_2 mitigation from different sources, especially the flue gas of coal-fired power plants (Fredrik et al., 2011). As suggested, CO_2-rich industrial flue gases can be fixated through the large-scale growth of microalgae (Langley et al., 2012). Tubular photobioreactors are considered as important and high-potential photobioreactors owing to their higher photosynthetic efficiency and biomass productivity. A hydrodynamic characterization of liquid and gas phases was performed by Fernandes et al. (2014), as well as the determination of the mass transfer coefficient of three different PBRs (bubble column and two split cylinder airlift photobioreactors (SCAPBR) with two different riser-to-downcomer cross sectional area ratios: SCAPBR 75 and SCAPBR50. SCAPBR50 (with a superficial gas velocity of 0.0044 ms/s) showed the highest value of biomass volumetric productivity (0.75 g/L day).

The effects of the cross-angle of two blades, horizontal spacing, open porosity, and hole radius of the novel static mixers on mixing characteristics were investigated by Cheng et al. (2016) to obtain appropriate configurations. Turbulent kinetic energy increased by 1.3 times and average velocity magnitude along the light direction increased by nearly 1000 times after adding novel static mixers into the tubular photobioreactor. A top-lit open microalgae bioreactor that uses a gas-lift system to enable deeper production depths, thereby significantly reducing the footprint, was developed by Seyed Hosseini et al. (2015). Growth of *Scenedesmus* sp. in a one-meter deep system sparged with 6% CO_2-enhanced air was evaluated. The results provided comparable volumetric biomass productivity (0.06 g_{dw}/L/day), but approximately three times higher areal productivity (60.0 g_{dw}/m^2/day) than reported for traditional raceways. A mathematical model using computational fluid dynamics (CFD) techniques is used to study the gas–liquid dispersion in an airlift reactor (Bannari et al., 2011). The new design of airlift gives a clear performance by the decrease of the

* Corresponding author.
E-mail address: juncheng@zju.edu.cn (J. Cheng).

http://dx.doi.org/10.1016/j.biortech.2016.09.071
0960-8524/

shear stress and increase of local and global mass transfer. The energy return of *Chlorella vulgaris* and *Dunaliella tertiolecta* cultivated in a gas sparged photobioreactor design was examined by Hulatt and Thomas (2011). Cultivation in 10 W/m^3 showed up to a 39% higher cumulative net energy return than that in 50 W/m^3 and increased the cumulative net energy ratio up to fourfold.

Gas aerators show an important effect on microalgal biomass growth (Loubiere et al., 2004; Liu et al., 2013). Whether a column reactor or a plate reactor, most closed PBRs aerate gas from bottom of the reactor (Chen et al., 2016; Yang et al., 2016b). Aeration gas resistance will be markedly increased as reactor height increases, especially new microbubble generator was used (Ying et al., 2013). A 75% reduction in aeration power input was obtained by reducing superficial gas velocity from 0.0210 to 0.0052 m/s at 5 400 ppm CO_2, without substantial reduction in biomass concentration (2.27–1.93 g/L, respectively) or productivity (0.189–0.173 g/L day, respectively) in airlift photobioreactors (Jones and Harrison, 2014). However, microalgae biomass sediment may be easily attached onto the surface of the reactor for slow solution velocity. Moreover, the gas outlet pressure of the industrial fan tends to be small.

For growing microalgal biomass with low energy consumption, a water-circulating column photobioreactor (WCC–PBR) was developed to decrease bubble generation time and mixing time. A high-speed photography system and online O_2/pH precise probes were used to measure bubble generation and residence times, mass transfer coefficient, and mixing time. The microalgal growth rate decreased by 12.7% from 10.7 mg/L/h in an air-lifting column photobioreactor (ALC–PBR) to 9.4 mg/L/h in a WCC-PBR because of a decreased residence time of bubbles and an additional shear of cells in a water pump. However, the total energy consumption of a WCC–PBR with an air compressor and a water pump was lower by 21.1% than that of an ALC–PBR with only an air compressor.

2. Materials and methods

2.1. Bubble diameter and velocity measurement with HSP

The schematic of the WCC–PBR, ALC–PBR, and HSP measurement area is shown in Fig. 1. The WCC–PBR was 2 m high and 0.15 m in diameter (Fig. 1a); instead of gas lift force, a water pump was used to circulate the culture solution. The ALC–PBR with 2 m height and 0.15 m in diameter is shown in Fig. 1b. Clean water was used during the experiment. The accurate pump solution velocity inside the circulation pipeline (pipeline solution velocity) was measured by weighing method (Yue et al., 2008). Pump solution volume ($V_{solution}$) from the pipeline was collected within a certain time (t); therefore, pipeline solution velocity ($v_{velocity}$) was calculated as: $v_{velocity} = V_{solution}/t/S$, where S is the cross section area of the circulation pipeline.

Bubble generation time and residence time was measured according to the method described in Cheng et al. (2015c). The rectangular areas filled with hatching lines represent the HSP measurement areas. For simplifying the calculation process, four calculation areas (9–12, Fig. 1c) were selected for the calculation. Ten bubbles were uniformly selected from each calculation area.

2.2. Measurement of mass transfer coefficient and mixing time

The overall volumetric mass transfer coefficient k_La_L was measured as described in Cheng et al. (2015b). The rates of N_2 and air aeration were controlled using a mass flow meter (SevenstarCS200, China). Dissolved oxygen (DO) concentration (C) versus time (t) was recorded with DO probes (InPro6850i/12/120 Mettler Toledo) every 0.2 s. Dissolved oxygen concentration range from

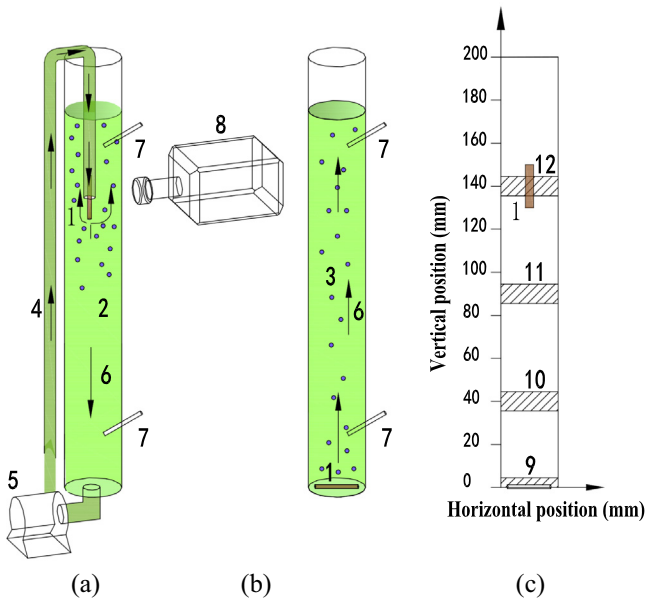

Fig. 1. Schematic of the experimental column photobioreactor and measurement systems. 1. Porous gas aerator, 2. water-circulating column photobioreactor, 3. air-lifting column photobioreactor, 4. circulation pipeline, 5. water pump, 6. solution in column photobioreactor and arrows represent flow directions, 7. two dissolved oxygen (DO) probes or pH probes, 8. high-speed photography with a CCD camera, 9–12. four measurement areas.

1 mg/L to 5 mg/L was used for calculation. The solution-phase mixing time (mixing time) was calculated as previously described by Mirón et al. (2004). During the test, pH of water was maintained at 2.7 ± 0.1 by adding hydrochloric acid (35%, w/v). A 10 mL volume of alkalinity tracer (12 mol/L NaOH solution) was added each time. The response to this pulse was measured with pH probes (InPro3253i/SG/120 Mettler Toledo) at two positions in the WCC–PBR or ALC–PBR.

2.3. Measurement of air compressor power consumption and aeration gas pressure

Compressed air was provided by an air compressor (TYW-2, Suzhou Tongyi Co., Ltd., China) with a rated power of 840 W. Under continuous running condition, the electromotor work time was marked as t_w, and the electromotor break time (between two adjacent work time) was marked as t_b. Therefore, the air aeration system energy consumption during the measurement process (air compressor power consumption) was calculated as: $p_{air} = p_o t_w/(t_b + t_w)$, where p_o is the rated power of the air compressor. The energy consumption of the ALC–PBR culture system was the same as the air compressor power consumption. The energy consumption of WCC–PBR culture system was equal to the total of air compressor power consumption and water pump power. Aeration gas pressure was measured with a gas manometer (YB-150B, Shanghai Automatic Meter Fourth Factory, China). Standard deviations of air energy consumption and pressure were calculated based on three independent measurements.

2.4. Microalgal cultivation

The WCC–PBR and ALC–PBR culture systems were used to carry out the microalgal culture experiment at 24 °C under continuous illumination of 40 000 ± 2000 lx. Microalgal strain *Chlorella* mutant *PY-ZU1* was cultured with Brostol's solution and measured using the method of Cheng et al. (2013). The culture medium was contin-