Bioresource Technology 207 (2016) 31–38

Contents lists available at ScienceDirect

Bioresource Technology

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

Enhancement of microalgae production by embedding hollow light guides to a flat-plate photobioreactor

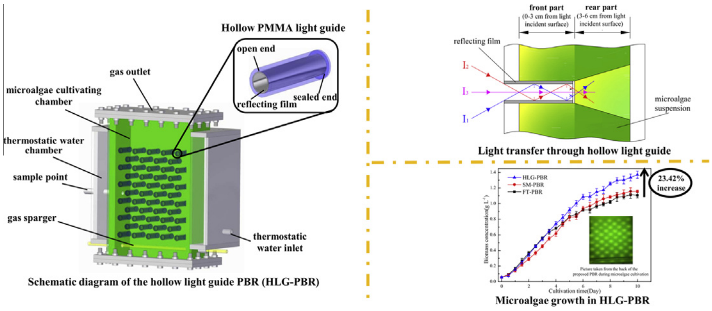
Yahui Sun, Yun Huang*, Qiang Liao, Qian Fu, Xun Zhu

Key Laboratory of Low-grade Energy Utilization Technologies and Systems, Chongqing University, Ministry of Education, Chongqing 400044, China
Institute of Engineering Thermophysics, Chongqing University, Chongqing 400044, China

HIGHLIGHTS

- Hollow PMMA tubes were embedded into a flat-plate photobioreactor as light guides.
- Average light intensity of interior regions was enhanced 2–6.5 times.
- The optimized light distribution induced a photosynthetic efficiency of 12.52%.
- Hollow PMMA tubes aroused additional mixing of the microalgae suspension.
- Biomass production in photobioreactor with light guides was increased by 23.42%.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 8 December 2015
Received in revised form 27 January 2016
Accepted 31 January 2016

Keywords:
Microalgae
Photobioreactor
Light attenuation
Hollow light guides
Photosynthetic efficiency

ABSTRACT

To offset the adverse effects of light attenuation on microalgae growth, hollow polymethyl methacrylate (PMMA) tubes were embedded into a flat-plate photobioreactor (PBR) as light guides. In this way, a fraction of incident light could be transmitted and emitted to the interior of the PBR, providing a secondary light source for cells in light-deficient regions. The average light intensity of interior regions 3–6 cm from surfaces with 70 μmol m^{-2} s^{-1} incident light was enhanced 2–6.5 times after 3.5 days cultivation, resulting in a 23.42% increase in biomass production to that cultivated in PBR without PMMA tubes. The photosynthetic efficiency of microalgae in the proposed PBR was increased to 12.52%. Moreover, the installation of hollow PMMA tubes induced turbulent flow in the microalgae suspension, promoting microalgae suspension mixing. However, the enhanced biomass production was mainly attributed to the optimized light distribution in the PBR.

1. Introduction

Global warming and fossil energy shortage are two primary global concerns. Technologies that can simultaneously solve both energy and environmental issues are in urgent demand. Microalgae is an important material for biological CO_2 fixation and biodiesel production and has inspired scientists worldwide due to its significant carbon dioxide capture capacity, high lipid content, non-competitive growth with arable land and usage in waste water and flue gas treatments (Chisti, 2007; Christenson and Sims, 2011; Mata et al., 2010; Thiruvenkadam et al., 2015).

For the cultivation of microalgae, photobioreactor (PBR) is an essential apparatus that can provide appropriate growth conditions, such as temperature, light and nutrients, for the proliferation of microalgae cells (Ugwu et al., 2008). The growth rate of microalgae cells is primarily affected by the light intensity absorbed by the cells during photoautotrophic cultivation in PBRs. However, in

---

* Corresponding author. Tel./fax: +86 23 65102474.
E-mail address: yunhuang@cqu.edu.cn (Y. Huang).

http://dx.doi.org/10.1016/j.biortech.2016.01.136

practice, the penetration depth of incident light within microalgae suspension decreases exponentially as the microalgae biomass concentration increases due to significant shading effects between microalgae cells (Anna et al., 2012; Posten, 2009). Regions far from the light source receive insufficient light intensity to maintain growth conditions and prevent the accumulation of biomass.

Various attempts have been made to alleviate the negative effect of light attenuation on microalgae growth. One approach is to expose microalgae cells to a sufficient number of photons by energy-intensive active stirring mechanisms or promote the mixing of microalgae suspension along light gradient by installing special static mixers in PBRs (Chisti, 2007; Huang et al., 2014; Janssen et al., 2000; Pruvost et al., 2008). For example, Huang et al. (2015, 2014) designed built-in mixers with small trapezoidal chamber units to increase the liquid velocity along the light gradient. The maximum biomass concentration was increased by 42.9%. However, because microalgae cells are sensitive to shearing stresses, the turbulence intensity induced by mixing should be controlled (Posten, 2009). Another way is to merely improve the incident light intensity. Wahidin et al. (2013) achieved a 20% increase in the maximum biomass concentration of *Nannochloropsis* sp. by increasing the light intensity from 50 to 200 μmol m^{-2} s^{-1}. However, Yen and Chiang (2012) demonstrated that even with an increase in incident light intensity from 1000 to 7000 μmol m^{-2} s^{-1}, the output light intensity penetrated through a 0.5 cm depth of microalgae suspension with a density of 2.6 g L^{-1} only slightly increased from 80 to 400 μmol m^{-2} s^{-1}. Typical cultivation depths are more than 3 cm for most enclosed PBRs and 15–35 cm for open raceway ponds (Zhao and Su, 2014). Therefore, the use of higher incident light intensity would hardly improve the light conditions for microalgae cells far from the light source. Additionally, the increased intensity of incident light would likely destroy the PS II complexes of the microalgae and subsequently decrease the biomass productivity of microalgae cultures (Brennan and Owende, 2010; Carvalho et al., 2011).

Thus, the optimization of transmitted light to microalgae suspension, especially to regions far away from light incident surface, remains an issue in PBRs (Singh and Sharma, 2012). Many innovative PBRs have been developed that use optical fibers (Chen et al., 2006; Xue et al., 2013) or planar scattering light waveguides (Ahsan et al., 2014; Jain et al., 2015; Jung et al., 2014) as internal light sources to provide better light homogeneity in PBRs. However, due to the large ratio of light emitting surface areas to light incident surface areas, light concentrating devices are necessary for optical fibers or planar waveguides. These considerations will increase the operational complexity and initial investment costs of PBRs.

In this study, cheaper cylindrical hollow polymethyl methacrylate (PMMA) tubes were fabricated and embedded into a flat-plate PBR as light guides to effectively deliver incident light to light-deficient regions. The light distribution in the PBR was analyzed, and performance comparison experiments between the proposed PBR and the conventional flat-plate PBR (FT-PBR) were also carried out under different incident light intensities and gas flow rates.

2. Methods

2.1. Microorganism and culture medium

The microalgae strain used in this study was *Chlorella vulgaris* FACHB-31, which was purchased from the Freshwater Algae Culture Collection of Hydrobiology, Chinese Academy of Science, China. Blue-Green medium (BG11) containing 1.5 g $NaNO_3$, 0.04 g K_2HPO_4, 0.075 g $MgSO_4{\cdot}7H_2O$, 0.036 g $CaCl_2{\cdot}2H_2O$, 0.006 g citric acid, 0.006 g ferric ammonium citrate, 0.001 g $EDTANa_2$, 0.02 g Na_2CO_3 and 1 mL trace metal solution in 999 mL distilled water was used as the cultivation medium. The trace metal solution contained 2.86 g H_3BO_3, 1.86 g $MnCl_2{\cdot}4H_2O$, 0.22 g $ZnSO_4{\cdot}7H_2O$, 0.39 g $Na_2MoO_4{\cdot}2H_2O$, 0.08 g $CuSO_4{\cdot}5H_2O$, 0.05 g $Co(NO_3)_2{\cdot}6H_20$ in 1 L of distilled water. For all cultivation experiments, the initial inoculated microalgae density in the PBRs was 0.06 g L^{-1} and the initial pH was adjusted to 7.1 ± 0.1 with 0.1 M HCl and 0.1 M NaOH. During the cultivation process, the pH was regulated by a continuous aeration of 5% CO_2 (v/v) gas (balanced with sterilized ambient air) according to the CO_2 dissolution equilibrium. Firstly, CO_2 dissolved in culture medium in the form of carbonic acid (H_2CO_3), which can be dissociated to hydrogen ion (H^+) and bicarbonate ion (HCO_3^-). And then bicarbonate ion (HCO_3^-) is further dissociated to hydrogen ion (H^+) and carbonate ion (CO_3^{2-}). The dissociation constants are mainly determined by temperature (Millero et al., 2006). Since temperature was kept at 28 ± 1 °C, thus the dissociation constants were constant, resulting in a near stable hydrogen ion (H^+) concentration in microalgae suspension. Therefore, the pH of culture medium was regulated at a near stable level during the growth of microalgae.

2.2. Design of the hollow light guide PBR

As shown in Fig. 1a, the proposed flat-plate PBR consisted of two separate chambers defined as a microalgae cultivating chamber and a thermostatic water chamber. The microalgae cultivating chamber (length: 180 mm, width: 60 mm, and height: 310 mm) was surrounded by the thermostatic water bath chamber. Fifty identical hollow PMMA tubes (external diameter: 12 mm, inner diameter: 10 mm) were embedded onto the front wall of the flat-plate PBR in a staggered arrangement (see Fig. 1a). The total cross section area of the hollow PMMA tubes accounted for 11.4% of the front wall area of the PBR. Aluminum-coated PET films with high reflectivity were adhered onto the inner surfaces of the hollow PMMA tubes (Fig. 1a). The aluminum-coated PET films in the inner surfaces of the hollow PMMA tubes can ensure that the light irradiated onto the inner surfaces of hollow PMMA tubes will be transmitted forward by the reflection of the high reflecting PET films. By this way, more incident light can be transmitted to the rear end of the PBR where light is insufficient for microalgae growth. The length of each hollow PMMA tube inside the cultivating chamber was 30 mm, i.e., half the width of the cultivating chamber (Fig. 1b).

The working principle of the hollow PMMA tube is described as follows. When light irradiates onto the open end of the tube, a fraction is transmitted forward via total reflection on the reflecting film (light paths I_1 and I_2 in Fig. 1b) and the remaining fraction is directly transmitted forward through air (light path I_3 in Fig. 1b). The transmitted light is then emitted from the sealed end of the tube directly onto microalgae cells in the rear end of the PBR. Compared with other simple methods to improve exposed light intensity of microalgae cells, the introduction of hollow PMMA tubes had the advantages of (i) fewer light sources and less electric energy input will be needed owing to an optimized light distribution by transmitting a fraction of incident light directly to light-deficient regions in HLG-PBR when compared with the both sided incident of light, (ii) photo-inhibition caused by exposing to excess light intensities using emerging high power light sources can be avoided and a higher photosynthetic efficiency can be obtained under lower incident light intensities, (iii) no additional heat will be generated by the introduction of hollow PMMA tubes and the complicated waterproof treatment for the submersed light sources will be needless when compared with the emerging underwater light sources.

Herein, we refer to the proposed PBR with hollow PMMA tubes for light transmission as a hollow light guide PBR (HLG-PBR). If all open ends of the hollow PMMA tubes were blocked with opaque,