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Consideration of inclined mixers embedded inside a photobioreactor for microalgae cultivation using computational fluid dynamic and particle image velocimetry measurement

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ABSTRACT

Microalgae have been introduced as one of the most promising alternative resource to substitute fossil fuels. Photobioreactors (PBR) are essential apparatus that facilitate cultivation of microalgae. In this study, a new PBR is designed and constructed based on internal mixing of microalgae to increase biomass productivity. The proposed PBR is equipped with hollow tubes which are simultaneously served as static mixer and internal light source to the culture. A PBR with the same geometry and without internal mixers is used as control PBR to evaluate the performance of this new system. The hydrodynamics inside both systems are simulated using 3D computational fluid dynamics (CFD). According to simulation results, the proposed PBR with static mixers has better performance in terms of fluid circulation, gas volume fraction and turbulency compared to the control system. Algal growth in the proposed PBR and the control system are compared through experimental cultivation tests. Microalgae cultured in the proposed PBR has higher growth rate compared to microalgae cultured in the control PBR at the same light intensity. According to experimental results, maximum biomass concentration in the proposed PBR is 100% higher than that in the control one which could be due to the better circulation of culture inside the proposed PBR. Analysis of the biomass obtained from both PBRs shows similar composition and heating value. However, the other properties of these samples such as volatile matter content, ash content and fixed carbon content are slightly different.

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1. Introduction

With the rise of environmental effects of fossil fuels and global increase in energy demand, renewable energy has received worldwide attention. Of all potential resources, microalgae has shown a promising potential due to higher photosynthetic efficiency, faster growth rate, high area specific yield and efficient CO_2 fixation. Besides, they can be cultivated not only in fresh water but also in saline environment and do not compete with productive lands (Azizi et al., 2017a; Chiaramonti et al., 2016; Suganya et al., 2016). Microalgae have numerous commercial applications and could be used as a nutritional value to improve animal feed or as feedstock for different industries (Chen et al., 2014).

For microalgae cultivation, PBRs are used for cultivation of high quality culture under controlled conditions with minimum potential of contamination (Pegallapati and Nirmalakhandan, 2013). In PBR, light passes through the reactor walls to reach the culture. The growth rate of microalgae is affected by the light intensity which is absorbed by algal cells. The penetration depth of light inside the microalgal culture decreases as the biomass concentration increases due to the shading effect of cells (Pegallapati and Nirmalakhandan, 2013). Thus, microalgae growth rate decreases in regions far from the light source. Therefore, developing cultivation systems which utilize the uses of light energy is an essential requirement.

Various attempts have been made to decrease the effect of light attenuation. One approach is to increase the incident light intensity. Rajanren et al. (2015) examined three different light intensities including 1500, 1800 and 2000 lux on growth of microalgae and they showed that the highest number of cells and biomass is

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produced at light intensity of 2000 lux. Although light intensity enhancement has positive effect on the microalgae growth, it is less effective at high cell densities. Yen and Chiang showed that when light intensity is increased from 1000 to 7000 μmol m^{-2} s^{-1}, the light intensity at the depth of 0.5 cm in microalgae culture with optical density (OD) of 3 is slightly increased from 80 to 400 μmol m^{-2} s^{-1} (Yen and Chiang, 2012). Therefore, light intensity increment would hardly improve photon absorption by microalgae cells at locations far from the light source due to high cultivation depth of PBRs and raceway ponds.

Application of internal illumination system in PBRs is another way to overcome drawbacks of light attenuation. Sun et al. (2016) embedded hollow tubes into a flat plate PBR as light guides and showed that biomass production and photosynthetic efficiency were increased by 23.42% and 12.52% respectively, compared to the same PBR without hollow tubes. Heining et al. (2015) used wireless light emitter as internal source and showed that internally and externally illuminated PBRs have the same growth rates in the exponential growth phase. However, they illustrated that growth rate of internally illuminated cells in the linear phase is twice more than the growth rate of externally illuminated cells.

The other approach to avoid light attenuation is to increase mixing of microalgae suspension so that algal cells are exposed to sufficient light intensity. Although gas flow rate could promote circulation of cells between different regions from dark regions to light ones and vice versa, Sun et al. (2016) showed that it has a slight effect on improving the total biomass concentration. Application of static mixers in the PBRs is another way to increase the mixing condition inside the reactors (Huang et al., 2015, 2014; Wang et al., 2014). It should be noted that algal cells are sensitive to shear stress. Therefore, turbulence intensity could have adverse effect on the microalgae growth.

CFD is a popular modeling technique which is widely used to simulate and analyze the performance of various processes. Simulation is specifically used as a tool to model flow behavior of a system and to predict the events which control that behavior (Bitog et al., 2014). Compared to experimental methods, CFD modeling has advantages such as cost saving, timely, safe and easy to scale up (Wang and Yan, 2008). CFD could be used to determine the hydrodynamic properties of microalgae culture such as fluid velocities, flow rates, dead zone and particle trajectory (Massart et al., 2014).

Huang et al. (2015) performed CFD simulation based on Eulerian two-phase model to evaluate the effect of using a special mixer in cultivation of microalgae. Their CFD results showed that strong local fluid circulation occurred in the trapezoid chambers within the novel PBR and it enhanced the mixing intensity along the light transfer direction which causes algal cells to circulate from the illuminated surface to the dark center. They also showed that turbulent kinetic energy (TKE) and volume-averaged turbulent kinetic energy dissipation of fluid in the novel PBR were much lower than those in the control PBR at the same air flow rate. Bioteg et al. (Pascual et al., 2014) optimized hydrodynamic parameters of cylindrical bubble column PBR using CFD simulation. Particle image velocimetry (PIV) was used as experimental procedure to validate numerical simulation. They showed that the most appropriate PBR for microalgae cultivation is a design with internal baffle and an extended cone-shaped bottom section due to lower dead zones and better mixing and mass transfer. Soman and Shastri (2015) proposed a novel PBR design and studied hydrodynamic performance of mentioned PBR using CFD to compare the performance of novel and conventional airlift PBRs. The results showed that the novel design had superior liquid circulation properties that improve the production efficiency and hence yield of microalgae. Massart et al. (2014) optimized an airlift PBR to enhance microalgae production by establishing and validating a CFD hydrodynamic model for a flat panel airlift PBR. Experimental water flow rates induced in the riser of the reactor and the liquid circulation were compared to the CFD solution. The numerical simulation results were in good agreement with experimental results which showed CFD was a useful tool to study flow behavior of PBR. It could be concluded that hydrodynamic characteristics play a key role to maximize microalgae production.

In the present study, a new configuration of bubble column PBR is proposed by embedding inclined light guides into the reactor. The mentioned inclined tubes act as not only mixer but also light source. The paper has a twofold purpose: numerical simulation of hydrodynamics inside PBR and experimental investigation of microalgae cultivation inside the proposed and control PBRs. In the first part, PIV is used to validate the CFD and to study hydrodynamic characteristics of the proposed PBR. Flow characteristics, including velocity, volume fraction and turbulence parameters (including TKE, turbulence dissipation rate (TDR) and turbulence viscosity) are determined and investigated in detail. In the second part, *Chlorella vulgaris* algal strain is cultured in the new designed and control PBR. Elemental composition of microalgae is characterized by ultimate analysis. Moisture content, volatile matter content, ash content and fixed carbon content of microalgae is determined by proximate analysis. Finally, FTIR analysis has been used to compare functional groups of species cultured in proposed and control PBRs.

2. Materials and methods

2.1. Description of PBR

A schematic diagram of bubble column PBR with inclined mixer and control PBR are shown in Fig. 1. Both PBRs are of the same size with internal diameter of 90 mm and the height of 600 mm and they both are made of pyrex glass. A gas sparger is placed at the bottom of each reactor.

As shown in Fig. 1, the proposed bubble column PBR consisted of a series of static mixers to attain a better mixing along the PBR height. The mentioned mixers are hollow and they are made of transparent glass, making them suitable choice to be used as light sources. In this case, better light distribution inside the PBR can be achieved with lower attenuation gradient in radial direction. The diameter and length of these mixers are 10 mm and 100 mm, respectively and twelve of them are placed symmetrically inside the PBR.

2.2. CFD simulation

Numerical simulations are based on two-fluid model Eulerian–Eulerian approach. Most of CFD simulations on bubbly flow in bubble columns are performed using the Eulerian–Eulerian approach (Bhusare et al., 2017; Li et al., 2009; McClure et al., 2015). The governing equations are summarized as follows. It should be noted that in this simulation it is assumed that the bubbles have the same size and are spherical.

The continuity equation for both phases ($q = l$ for liquid and g for gas) is given by

$$\frac{\partial}{\partial t}\left(\alpha_q \rho_q\right) + \nabla \bullet \left(\alpha_q \rho_q \vec{v}_q\right) = 0 \tag{1}$$

where α_q is the volume fraction of liquid or gas phase, ρ is density and v is velocity. The conservation of momentum is described by:

$$\frac{\partial}{\partial t}\left(\alpha_q \rho_q \vec{v}_q\right) + \nabla \bullet \left(\alpha_q \rho_q \vec{v}_q \vec{v}_q\right) = -\alpha_q \nabla p_q + \nabla \bullet \overline{\tau}_q + \alpha_q \rho_q \vec{g} + \sum F_q \tag{2}$$

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