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Numerical simulation on promoting light/dark cycle frequency to improve microalgae growth in photobioreactor with serial lantern-shaped draft tube

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ABSTRACT

Computational fluid dynamics were employed to simulate microalgal cells movement with enhanced flash-light effects in a gaslift loop-current column photobioreactor (GLCP) with serial lantern-shaped draft tube (LDT). Clockwise and anticlockwise vortexes were formed in outer down-flow region of GLCP with LDT. The radial velocity, axial velocity, and turbulent kinetic energy of microalgal solution appeared periodical change around the lanterns. The average radial velocity showed a sixfold improvement from 0.003 m/s to 0.021 m/s, and average turbulent kinetic energy was enhanced by 18.2% from 22.5×10^{-4} m^2/s^2 to 26.6×10^{-4} m^2/s^2, thus increasing light/dark cycle frequency by 54%. The light/dark cycle frequency increased first and then decreased with an increase of individual lantern height. The increased lantern number promoted the light/dark cycle frequency and light time ratio. Microalgal biomass yield in the GLCP with LDT was improved by 30%, and CO_2 fixation peak rate was promoted by 35%.

1. Introduction

CO_2 is a greenhouse gas that mainly causes global warming and contributes to the formation of hostile environments (Chiaramonti et al., 2013; Yi et al., 2015). Microalgae can biologically utilize and convert CO_2 to high-added biomass. Using microalgae to mitigate CO_2 emissions is feasible and prospective (Alhamed et al., 2014). Thus, it is essential to develop the photobioreactors that cultivate microalgae. Light intensity varies inside the microalgae solution in the photobioreactors due to the attenuation phenomenon in liquid phase. Moreover, the growth of microalgal cells is slow in dark zones. An appropriate mixed multiphase flow state in photobioreactors is pivotal to the efficient supply of CO_2 efficiently, elimination of produced oxygen, provision of alternating periods of light/dark cycles, equal distribution of nutrients, and avoidance of cell sedimentation (Yang et al., 2014). The influence of light/dark cycles with different light intensities on the growth of microalgae has been widely investigated (Grobbelaar, 1994; Grobbelaar et al., 1996). The vivid characterization of flow field in photobioreactors via experiment is difficult and costly to achieve. The developments of computational fluid dynamics (CFD) and the availability of more powerful computers have paved the way for the modeling and design of bioreactors (Bannari et al., 2011; Bitog et al., 2011). Hadiyanto et al. (2013) evaluated the hydrodynamic characteristics of algal raceway pond, such as variation in fluid velocity, shear stress. Massart et al. (2014) studied a bioreactor that combined flat-plate bioreactors and airlift. The properties of alternative and regular exposures to light/dark regions of the bioreactor were identified by CFD.

Gaslift column photobioreactors are widely adopted in microalgal cultivation due to their advantages, such as good mixing and mass transport, low power consumption, low shear stress, decreased photoinhibition and photooxidation (Saeid and Chojnacka, 2015). The flow of fluid in the gaslift column photobioreactors is driven by buoyancy resulting from the up-flow of gas bubbles in such bioreactors. The hydrodynamics of a bubble column, including average circulation time and turbulence intensity, were investigated by CFD and then verified by particle image velocimetry (Bitog et al., 2014). However, the flow field was not arranged well. Kaewpintong et al. (2007) developed a gaslift loop-current column photobioreactor (GLCP) with a straight draft tube (SDT), the structure of which was verified to form a loop-current flow pattern in contrast to the disorder flow mode in usual bubble column photobioreactor. The following researches (Eze et al., 2017; Hosseini et al., 2015; Luo and Al-Dahhan, 2008) has performed profound studies on the hydrodynamics (fluid velocities, superficial gas velocities, shear rate) of GLCP, and verified the flow field of this type of photobioreactor was able to obtain three-times higher growth rates than those reported for traditional raceways. However, GLCP with SDT still suffered from several serious drawbacks. For example, the flow pattern in a GLCP with SDT was investigated by CFD (Calvo et al., 2017; Gao et al., 2018; Pawar, 2018), and the loop flow pattern was approved. However, the

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small turbulent kinetic energy and the layer flow in outer down-flow region of GLCP with SDT resulted in low radial velocity and small light/dark cycle frequency. Microalgal cells in dark zone show poor photosynthesis, which led to a small growth rate and CO_2 fixation rate. Furthermore, poor mixing of nutrients due to laminar flow with SDT was also undesirable for microalgal growth (Huang et al., 2015a). So, the construction of GLCP with a draft tube had to be redesigned to improve flow field in out down-flow region. A Taylor vortex reactor with a rotating SDT was developed by Kong et al. (2013) and was further investigated by Gao et al. (2015). This photobioreactor achieved a high microalgal biomass yield, but it expended a large amount of electricity. However, little research focused on flow field enhancement via the structure optimizing of draft tube. It is an energy-efficient and effectual way to obtain good performance of photobioreactors. Ye et al. (2018) developed a serial lantern-shaped draft tube (LDT) that produced vortexes to improve the radial velocities of microalgal cells between light and dark areas in a GLCP and consequently increase biomass yield by 50%. However, the PIV measurement can only reveal the flow field in a local and small area. The global flow field and vortexes distribution in the GLCP with LDT were not comprehensively revealed due to the limitations of experimental measurement method. By the same token, the fluid turbulent kinetic energy, microalgal cells movement and light/dark cycle frequency were left unexplored, as well as the effect of LDT structures on the light/dark cycle frequency.

In the present study, the movement of algal cells in the vortex flow field produced by serial lantern-shaped draft tube (LDT) was analyzed through CFD. The overall and local flow field in the GLCP with LDT were depicted in detail. The fluid velocity, turbulent kinetic energy, cell light/dark cycle frequency and light time ratio were investigated. The effects of LDT structures on the light/dark cycle frequency were also evaluated. The results demonstrated that LDT can arrange a good vortex flow field, enhance flash-light effect, thereby facilitate microalgae growth, together with CO_2 fixation rate.

2. Materials and methods

2.1. Geometries of the GLCP and LDT and the coordinate system

The geometries of the GLCP with LDT was showed in Fig. 1(a). The height of GLCP was 600 mm with the diameter of 130 mm. The microalgal solution depth was 575 mm. The height of LDT was 535 mm. The diameters of two ends were both 35 mm. The individual lantern height (H_i) at various experimental settings were 15, 20, 25, 27, 30 mm. So, (H_i + 35) mm was the biggest diameter of LDT. LDT consisted of four to eight lanterns due to different settings. The axis of LDT was placed coincided with the axis of the GLCP. Moreover, the bottom of LDT was 20 mm above the bottom of the GLCP. A gas aerator with a diameter of 5 mm introduced bubbles into microalgae liquid. The bullseye of gas aerator was set coincided with the bullseye of the bottom of the GLCP. The flow field is split to 2 connected regions by LDT: outer down-flow area and inner tube up-flow area. The GLCP with SDT was applied as the control group as showed in Fig. 1(c). SDT had the same end-diameter of 35 mm with LDT, while the middle-diameter was 60 mm. The middle size was determined on the basis of the average value of the minimum and maximum diameters of LDT (H_i = 25 mm). The coordinate system was set as that shown in Fig. 1(b). The original point (0, 0, 0) was set at the central bottom of GLCP, and the positive directions of the x-and y-axes were rightward and upward, respectively.

2.2. Flow simulation condition

As a result of the considerable symmetry of GLCP with LDT, a 2D mesh of the GLCP was established using ANSYS ICEM CFD (64 bit, ANSS, Lnc. USA) software, and the simulation was performed using ANSYS FLUENT 15.0 (64 bit, ANSS, Lnc. USA). The Eulerian two-phase model was engaged to simulate liquid flow in the bioreactor, because using the multiphase model was unavoidable while bubbles occur in the photobioreactors. The equations of continuity and conservation of momentum equations are given by:

$$\frac{\partial(\alpha_i\rho_i)}{\partial t} + \nabla\cdot(\alpha_i\rho_i\vec{u_i}) = 0 \quad (1)$$

$$\frac{\partial(\alpha_i\rho_i\vec{u_i})}{\partial t} + \nabla\cdot(\alpha_i\rho_i\vec{u_i}\vec{u_i}) = -\alpha_i\nabla p + \nabla\cdot(\alpha_i\mu_{eff,i}(\nabla\vec{u_i} + (\vec{u_i})^T)) + \alpha_i\rho_i\vec{g} + M_{l,i} \quad (2)$$

where t denotes time, α_i, ρ_i, $\vec{u_i}$ denotes the phase volume fraction, density, and the phase velocity for liquid (i = l) or gas (i = g), respectively. P is the pressure field, $\mu_{eff,i}$ represents the effective viscosity for liquid (i = l) or gas (i = g), g is the gravitational acceleration vector, and $M_{l,i}$ is liquid-gas momentum exchange force.

A RNG k-ε turbulence model was selected with first-order exactness to describe the turbulent flow behavior, and the turbulent dispersion force and drag force of gas-liquid interphase were considered. About the boundary conditions, the gas outlet was set with a degassing boundary, representing that only the gas in the dispersed phase could escape from the surface, and the continuous phase could not go through the top surface (Huang et al., 2015b). The outer walls and the internal structures of the GLCP were set to no-slip boundary condition to water. The time step for the transient flow field computation was set to 0.004 s. To confirm grid independency, three scale grids (14,358, 24,400, and 31,657) were used. Small difference was observed between the computed values of 24,400 cells and 31,657 cells. So, the mesh with 24,400 cells was adopted for all the cases.

2.3. Flow field and light/dark cycle frequency

Flow field (velocity magnitude contours and velocity vector diagrams of microalgal solution) in the GLCP was processed using Tecplot 360 EX 2015 (64 bit, Tecplot, Inc. USA) on the basis of the simulation result. The fluid radial velocity (V_x) and axial velocity (V_y) were calculated using the velocity magnitude and direction at various points on the L_1 [shown as a blue line in Fig. 1(b)]. Line L_1 was x = 43 mm from point (X = 43 mm, Y = 0 mm) to point (X = 43 mm, Y = 575 mm). The turbulent kinetic energy was also obtained from various points on line L_1. A total of 12 particles representing microalgal cells were injected from the entrance port. The port was the line from (−5 mm, 1 mm) to (5 mm, 1 mm). The particle diameter was 10 μm with a density of 1000 kg/m^3. The maximum particle tracking time was set to 50 s. Discrete random walk model (Perner-Nochta and Posten (2007)), drag force ($\frac{1}{8}\pi\rho d^2 C_D\,|\vec{v_f}-\vec{v_p}|(\vec{v_f}-\vec{v_p})$), and pressure gradient force ($\frac{\pi d^3\rho_f}{6}\frac{d\vec{v_f}}{dt}$) (Luo and Al-Dahhan, 2011) were considered during the simulation. where d was the particle diameter, ρ was its density, and $\vec{v}$ was the velocity vector, and subscripts p and f denoted particle and fluid, respectively. The particle position coordinates were recorded every 0.1 s. In our previous studies, the critical depth from light zone to dark zone was tested to be 2 cm when the microalgal concentration was 1.5 g/L (Yang et al., 2016). Thus, the middle concentration of 1.5 g/L at the exponential phase was chosen to investigate the law of the light/dark cycle frequency in the GLCP with LDT and SDT. So, the boundaries of light zones and dark zone were set as lines x = ± 45 mm, which divided the entire GLCP into two light zones (x ≤ −45 mm and x ≥ 45 mm) and one dark zone (−45 mm < x < 45 mm). Light/dark cycle period of a microalgal cell was defined as $t_c = t_l + t_d$, where t_c was the time for one light/dark cycle period; t_d and t_l represented the duration in which the microalgal cell resides in the dark and the light zones, respectively. The light/dark cycle period (T^i_{av}) of a microalgal cell was defined and calculated following the method described by Yang et al. (2016). The average light/dark cycle period of each cell was employed to compute the average light/dark cycle period of the whole population (T^p_{av}). $T^p_{av} = \lim_{N\to\infty}\left(1/N\cdot\sum_{i=1}^{N} T^i_{av}\right)$, where N is the number of