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Design and optimization of a novel airlift-driven sloping raceway pond with numerical and practical experiments

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ABSTRACT

A novel airlift-driven sloping raceway pond (ALSRWP) was proposed in this study. In order to increase the mixing degree and decrease the energy consumption, airlifting system and the sloping channels were combined. CFD (computational fluid dynamics) was used to simulate the mixing and light regime in the ponds. The hydrodynamic characteristic of three types of ALSRWPs and the control that is a conventional raceway pond (RWP) was compared in detail. The results showed that the ALSRWP fitted with airlifting system and sloping channels (1.55°) increased the average fluid velocity, promoted the velocity along the light attenuation direction, reduced the energy consumption, and significantly eliminated the dead zone compared with the conventional RWP. Lastly, three trials of cultivation experiments with *Chlorella pyrenoidosa* were conducted. The results showed that the dry cell weight in type III ALSRWP was 27.14% (0.89 g L^{-1}) higher than that in the control pond (0.70 g L^{-1}). In addition, and P_a (biomass areal productivity) in type III ALSRWP (10.52 g m^{-2} d^{-1}) was 37.34% higher compared with that in the control pond (7.66 g m^{-2} d^{-1}), indicating that type III ALSRWP could produce more biomass than others ponds under the same culture condition.

1. Introduction

With the depleting of fossil fuels and the emerging ill influence of greenhouse on environment and human society, biodiesel has attracted much more attention from science and industry. Microalgae are a new promising and sustainable feedstock for biodiesel production. The simple structure allows them to grow rapidly in theory [1]. Other benefits from microalgae include as a healthy food [2], bio-strainers to remove pollutants from sewage [3]. They are also commonly as a potential source of valuable chemicals such as pigments and cosmetics [4].

Cultivations of microalgae always were carried out in the vital devices called photo-bioreactors (PBRs). Generally, PBRs were divided into open ponds systems and closed culture systems. The construction, operation and maintenance of closed PBRs is always excessive, and their scalability is relatively poor. Presently, Open ponds system such as raceway ponds (RWPs) are the most frequently-used system for commercial biomass production of microalgae [5]. The salient advantages of open ponds system include simple structure, easy to operate and scale-up. However, compared with the closed PBRs, open pond systems are less efficient in the view of productivity due to their several factors, such as CO_2 deficiencies, poor mixing and light limitation [3]. Besides, there are some other drawbacks of this system, including vulnerable to be contaminated, low algal density lead to high cost of harvesting and so on [6].

In the course of the recent a few decades, computational fluid dynamics (CFD) technology has been widely used in the design and optimization of PBRs. CFD is considered as a low cost and high efficiency tool which has great impact on the breakthrough of the restriction between field analysis and laboratory experiments [7].

The main structure of raceway pond has little change for a long time. However, in recent years, great efforts have been made to find the way of reducing the energy consumption and improving the productivity. Liffman et al. [8] reported a novel bend of RWP devised by using CFD can reduce the energy loss of 87% compared to traditional bend. Zeng et al. [9] found that the raceway pond with inclined paddle wheels of 15° had the better mixing efficiency compared to that with traditional paddle wheel. A raceway pond with the combination of sloping baffles and deflectors was designed [10]. Nevertheless, modification of RWP with paddle wheel cannot meet the demand of reducing energy input and improving the utilization of light [11]. Ketheesan et al. [12] developed an airlift-driven raceway which can cut down energy requirement as much as 80% compared with the paddlewheel-driven RWP.

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Airlift system is used commonly as a gas-liquid contactor because of its ability of handling huge quantities of liquid based on the gas continuously push through the broth. In addition, it can provide gentle and homogeneous hydrodynamic shear [13]. Additionally, the sloping channels allow light penetrate into different depth of culture, making different zones at same horizontal level with different illumination levels. Microalgae cells will experience different illumination levels when they are moved by flowing fluid, which can dramatically improve the efficiency of sunlight utilization by algal cells.

In the present work, a novel airlift-driven sloping raceway pond (ALSRWP) was developed. The hydrodynamic characteristics and light regimes within different types of ALSRWPs and conventional raceway pond were calculated by CFD. These numerical results of hydrodynamic and light regimes characteristics in different ponds were further compared with each other in detail and analysed deeply. In addition, the structures of ALSRWPs were optimized. Lastly, the microalgae photoautotrophic cultivation tests were conducted outdoor to verify the results drew by theoretical analysis.

2. Material and methods

2.1. Geometries of airlift-driven sloping raceway pond

The schematic diagram of three ALSRWPs with different structures was shown in Fig. 1. The ALSRWP mainly consisted of two parts: one part was the flat channel; the other was the sloping channel. The flat part was served as the airlift system which was fitted with a central partition to serve as a U-tube with a downcomer and a riser. The sparger was placed at the bottom of the riser. CO_2-enriched air was constantly sparged into the culture broth. The density of the air-liquid mixture within the riser is less than that within the downcomer, which makes the fluid flow around the pond.

The tilt angle of sloping channel in type I, type II and type III of ALSRWP is 6.17°, 1.55°, and 1.55°, respectively. The area of ALSRWP is 1.5 m^2, which is equal with that of the conventional raceway pond as the control. The width and height of type I, type II and type III ALSRWPs are 1850 mm and 800 mm, respectively. In terms of length, type I and type II is 2150 mm, while type III is 2450 mm due to it fitted with two bends on both sides. The details of the structural parameters of ALSRWPs and the control RWP are shown in Fig. 2. Twenty small pores with a diameter of 0.5 mm were scattered evenly over the sparger.

2.2. Simulation model and numerical details

2.2.1. Theory of CFD simulation

The mixing performance and cell trajectories in the ponds were numerically simulated with ANSYS CFX 12.1 (64 bit). The gas-liquid flow in the ALSRWPs was simulated by the model of Eulerian two-phase. The governing equations for the gas-liquid system consisted of a set of continuity and momentum equations for each phase as follows.

Continuity equation:

$$\frac{\partial \rho_i \alpha_i}{\partial t} + \nabla \cdot \rho_{i\alpha_i} \boldsymbol{v} = 0 \tag{1}$$

Where

$$\sum_{i=1}^{2} \alpha_i = 1 \tag{2}$$

Momentum transfer equation:

$$\frac{\partial \rho_i \boldsymbol{v_i} \alpha_i}{\partial t} + \nabla \cdot \rho_i {\boldsymbol{v}_i}^2 = -\alpha_i \nabla \cdot \rho + \nabla \cdot (\alpha_i \tau_i) + \nabla\left(\alpha_i \rho_i {\boldsymbol{v_i}}^2\right) + \rho_i \boldsymbol{g} \alpha_i + \boldsymbol{F_{ij}} \tag{3}$$

where ρ is the fluid density, α is the volume fraction, t is the flowing time, $\boldsymbol{v}$ is the fluid velocity vector, $\boldsymbol{g}$ is the gravity acceleration, $\boldsymbol{F}$ is the interfacial momentum exchange term, and τ is the viscous stress tensor. The subscripts i and j represent the parameters in different phases.

2.2.2. Mesh generation

Three-dimensional meshes of the pond were created by ANSYS ICEM CFD 12.1 (64 bit). In order to avoid the simulation results affected by the number of grid [14], the grid-independent verification was conducted. An unstructured mesh of approximately 0.256 million, 0.524 million, 1.04 million, 1.94 million tetrahedron cells was generated for each PBR. The results of grid-independent verification were shown in Table 1. In comparison with the average flow velocity under condition of 1.94 million cells, error of 45.0%, 27.5%, and 5.5% was found in the simulated values of average flow velocity at mesh grid number of 0.256 million, 0.524 million, 1.04 million, 1.94 million, respectively. Eventually, the numbers of grid 1.04 million were used to calculate the hydrodynamic in pond, taking into account the accuracy of the calculation results and computational load.

2.2.3. Boundary conditions

The Eulerian two-phase model was applied since using multiphase model was inevitable when energy provided by airlift system in the ALSRWPs. The dispersed phase zero equation of standard k-ε model was adopted to describe the turbulent flow behavior in the ponds. Gas-liquid interphase drag force, lift force, virtual mass force, wall lubrication force and turbulent dispersion force was considered in the model, the drag force, lift force, virtual mass force, wall lubrication force and turbulent dispersion were set as grace, lift coefficient of 0.5, virtual mass coefficient of 0.5, Antal and Lopez de Bertodano. For high inlet air flow, the bubble induced turbulence has also been taken into account. Wall function "scalable" was applied to obtain a satisfactory result near the wall. The boundary condition of the top was setting as "opening", which meant that both the gas and liquid could escape from the surface freely. To simulating the free surface of water flow, the VOF (Volume of fluid) model was employed to simulate the surface fluctuation. The outer walls and the internal structures of the ponds were set to no-slip boundary condition to water.

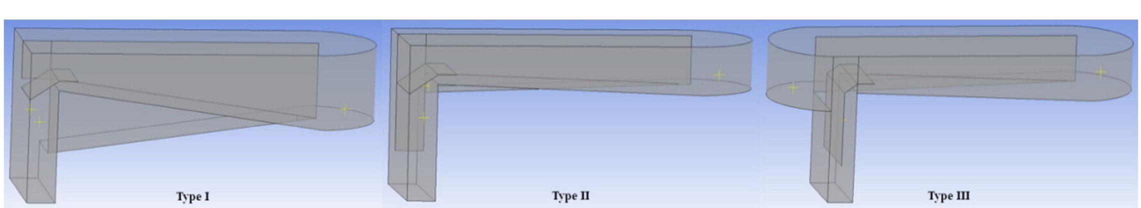

Fig. 1. Schematic diagram of airlift-driven sloping raceway pond with different structures.