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Development of a novel multi-column airlift photobioreactor with easy scalability by means of computational fluid dynamics simulations and experiments

Jianke Huang[a,1], Jiangguo Ying[a,1], Fei Fan[a], Qijian Yang[a], Jun Wang[b], Yuanguang Li[a,*]

[a] State Key Laboratory of Bioreactor Engineering, East China University of Science and Technology, Shanghai 200237, PR China
[b] JiaxingZeyuan Bio-products Co., Ltd., Jiaxing 314007, PR China

HIGHLIGHTS

- A scalable 300 L vertical multi-column airlift reactor was designed.
- Hydrodynamics including irradiation and shear stress were studied by CFD.
- Optimal operation manner and structure of the novel reactor were determined.
- Superiority of the optimized PBR was validated by cultivation experiments.

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ABSTRACT

Aiming to culture algae with high efficiency, a novel vertical multi-column airlift photobioreactor (VMAPBR) has been developed. It was constructed with a series of vertically arranged parallel columns with easy scalability. The hydrodynamic, irradiation and shear stress characteristics of the photobioreactor were studied by computational fluid dynamics (CFD). Accordingly, the optimal aeration manner and aeration rate were determined. When the novel airlift PBR was alternately aerated with aeration rate of 0.2 vvm, the biomass concentration of Chlorella pyrenoidosa under outdoor condition reached 1.30 g L^{-1} within the prototype PBR and was further increased to 1.56 g L^{-1} within the optimized PBR. The result of cultivation experiment had good agreement with that of CFD prediction.

1. Introduction

The phototrophic growth of microalgae integrates lipids accumulation, carbon dioxide elimination, waste water treatment, and high value compound production (Spolaore et al., 2006). Furthermore, microalgae can grow fast without consuming arable land, thus they are considered to be ideal source of renewable biodiesel (Chisti, 2007). Aiming to commercialize the merits of microalgae, much attention has been paid to the research of strain selection, medium optimization, photobioreactor design, harvesting process and so on. A photobioreactor (PBR) is a system that provides microalgae with proper light, temperature, pH, essential nutrition and a carbon source. The development of a large scale and high efficiency photobioreactor is one of the keys to realize commercial application of microalgae. Thus the research on design, optimization, and scale up of PBRs has received much attention in recent years (Zittelli et al., 2013).

Computational fluid dynamics (CFD) is a powerful tool used to study hydrodynamics in reactors by numerically solving Navier-Stokes equations. Using CFD, the fluid flow and irradiance characteristics inside PBRs can be recognized accurately and conveniently. The CFD simulation greatly accelerates the process of PBR development and thus becomes one of the forefronts in designing PBRs (Bitog et al., 2011). Huang et al. (2015a,b) designed a series of flat plat PBRs and raceway ponds with a novel inner structure. The prediction results made with CFD simulation were basically consistent with the results of algae cultivation experi-

* Corresponding author at: Mail Box 301, Meilong Road 130, Shanghai 200237, PR China.
E-mail address: ygli@ecust.edu.cn (Y. Li).
[1] Contributed equally to the work.

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ments. Perner-Nochta and Posten (2007) simulated single-phase mixing in tubular PBRs to calculate the particle trajectories that represent the path of algal cells, and analyzed the light/dark cycles by means of Wavelet and Fast Fourier Transform.

CFD simulation has also been applied to the research of airlift/bubble column photobioreactors which have the advantage of simple construction, inexpensive operational cost, and low energy input requirements. Luo et al. (2011) evaluated the reliability of using CFD simulations to trace the trajectories of microalgae in a draft column PBR. The inner structure of cylindrical airlift PBR was optimized by using CFD and further validated by microalgae cultivation (Xu et al., 2012). Soman and Shastri (2015) proposed and optimized a novel PBR which combined airlift and flat plate designs using CFD. With the assistant of CFD, many novel simulation methods and better PBR structures have been proposed, which lay the foundation for further developing the airlift/bubble column PBRs.

However, the airlift/bubble column is more considered as a laboratory-scale device or inoculum production system rather than a large-scale algae production system due to the difficult scalability. The scale up of an airlift/bubble column reactor is hard, mainly because the increment of diameter leads to serious attenuation of light along the radial direction, while the increment of column height decreases the axial mixing rate and calls for high construction costs (Janssen et al., 2002). According to Zitelli et al. (2006), a large number of column bioreactors properly deployed would be necessary for large scale production. However, for each unit, separate control devices for pH, temperature, aeration, carbon dioxide and nutrients supply would make a production "farm" much more labor-intensive and costly.

Difficulty in scale up hampers the practical application of airlift/bubble column PBRs for the industrial production of algae, therefore better PBR types and a scale up strategy need to be developed. In addition, most of the existing CFD simulation work on airlift PBRs lack the validation of microalgae cultivation, or the cultivation experiments were performed in almost indoor conditions, which left the performance of designed or optimized PBRs under complex outdoor conditions still unclear.

In the present study, a novel multi-column airlift PBR was developed which has a volume of 300 L and good scalability. CFD simulation has been performed on the novel PBR to quantitatively understand its hydrodynamics, irradiation and shear stress conditions under different aeration manners and rates. Thus optimal aeration manner and rate were determined. In addition, aiming to improve the irradiation surface and mixing along the light attenuation direction inside the PBR, the structure of the novel PBR was further optimized by reducing the diameter of vertical columns from 0.15 m to 0.10 m while sustaining the same volume. Lastly, the superiority of optimized PBR over the prototype PBR was validated by both CFD simulation and algae cultivation experiments under outdoor conditions.

2. Materials and methods

2.1. Description of the novel PBR

2.1.1. Geometries of novel PBR

As shown on Fig. 1, the novel multi-column airlift PBR consists of three parts: the vertical multi-columns in the middle, the horizontal bottom trough which connects bottom of the multi-columns, and the horizontal top trough which connects the top of the multi-columns. All these parts are made of completely transparent polyacrylamide with wall thickness of 3 mm, and are welded together compactly.

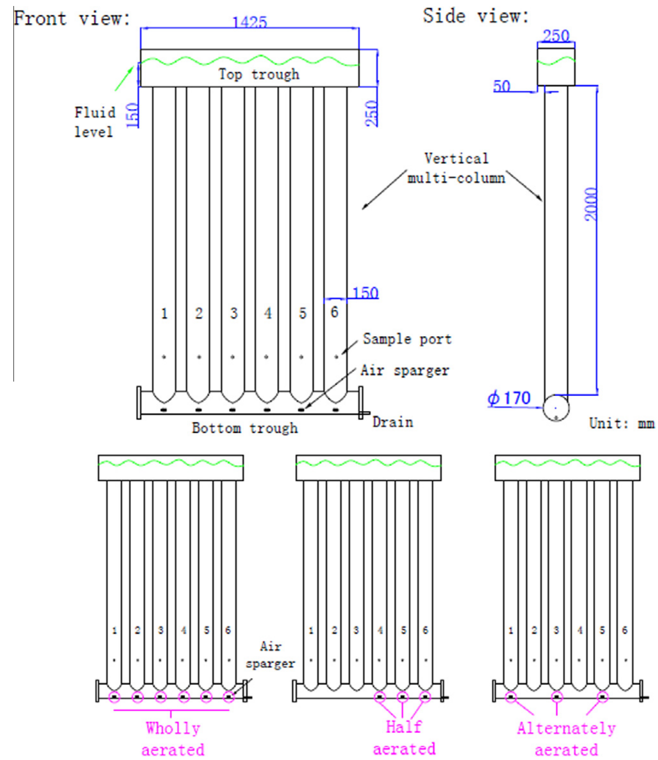

Fig. 1. The geometry and three aeration manners of novel multi-column airlift PBR.

The vertical multi-column airlift PBR (prototype) contains six vertical columns with lengths of 2 m and inner diameters of 0.15 m, which are arranged in a same vertical plane. Each vertical column has a sample port or CO_2 injection port near its bottom. The bottom trough is a cylinder which has the diameters of 0.17 m, lengths of 1.42 m and is sealed by flanges in both ends. Air spargers are fixed at the lowest region of the bottom trough concentric to the upside vertical column. The top trough is a cuboid which has the lengths of 1.42 m, width of 0.25 m, and heights of 0.25 m. Fluid will reach 3/5 of the height of the top trough to give the PBR a total volume of 300 L.

This novel prototype PBR was further optimized by reducing the inner diameter of vertical columns from 0.15 m to 0.10 m. The optimized PBR has the same height and same volume (300 L) as the prototype PBR. However the number of vertical columns increased from six to fourteen. Relatively, the length of bottom trough and top trough increased from 1.42 m to 2.37 m, while the inner diameter of bottom trough decreased to 0.12 m, and the width of top trough decreased to 0.20 m. The present novel PBR can be easily scaled up by up-numbering the vertical columns along the horizontal direction.

2.2. Aeration manners of the novel PBR

Based on the configuration, the airlift PBRs generally have two circulation patterns, the internal loop circulation and the external loop circulation (Singh and Sharma, 2012). For the presented multi-column reactor, it is necessary to make sure how the fluid will circulate inside the PBR.

The fluid inside the present PBR can circulate in different patterns depending on the manner of aeration that used. If all the vertical columns are evenly aerated by air, the fluid may internally circulate in each column, with upward movement near the cylinder axis and downward movement near the walls. If right half columns are aerated, the fluid may externally circulate between left