Bioresource Technology 119 (2012) 300–305

Contents lists available at SciVerse ScienceDirect

Bioresource Technology

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

Development of a draft-tube airlift bioreactor for *Botryococcus braunii* with an optimized inner structure using computational fluid dynamics

Ling Xu [1], Rui Liu [1], Feng Wang, Chun-Zhao Liu *

National Key Laboratory of Biochemical Engineering, Institute of Process Engineering, Chinese Academy of Sciences, Beijing 100190, PR China

HIGHLIGHTS

- An airlift reactor was designed using computational fluid dynamics (CFD).
- An airlift reactor for algal culture was scaled up to 40 L using CFD simulation.
- CFD provides a powerful means for the design and scale-up of algal culture reactors.

ARTICLE INFO

Article history:
Received 13 April 2012
Received in revised form 24 May 2012
Accepted 24 May 2012
Available online 1 June 2012

Keywords:
Airlift bioreactor
Botryococcus braunii
Computational fluid dynamics
Scale up
Optimization of structural parameters

ABSTRACT

The key parameters of the inner structure of a cylindrical airlift bioreactor, including the ratio of the cross-section area of the downcomer to the cross-section area of the riser, clearance from the upper edge of the draft tube to the water level, and clearance from the low edge of the draft tube to the bottom of the reactor, significantly affected the biomass production of *Botryococcus braunii*. In order to achieve high algal cultivation performance, the optimal structural parameters of the bioreactor were determined using computational fluid dynamics (CFD) simulation. The simulated results were validated by experimental data collected from the microalgal cultures in both 2 and 40-L airlift bioreactors. The CFD model developed in this study provides a powerful means for optimizing bioreactor design and scale-up without the need to perform numerous time-consuming bioreactor experiments.

1. Introduction

Phototrophic bioprocesses have been shown to be powerful tools for the production of valuable compounds from microalgae, and numerous bioreactors were designed for the large-scale cultivation of phototrophic microalgae. Airlift column reactors are widely used in chemical, petrochemical, and bioprocess industries because of their simple construction, inexpensive operational cost, and low energy input requirements (Pollard et al., 1998; Heijnen et al., 1990). Recent research reported the successful utilization of airlift reactors in microbial fermentation for the production of chemical, such as 1,3-dihydroxyacetone, ethanol, and poly 3-hydroxybutyrate (Hu et al., 2011; Lennartsson et al., 2011; Pradella et al., 2010). Airlift reactors allow for rapid mixing while producing weak shear stress, which makes them suitable for microalgae cultures (Xu et al., 2009; Camacho et al., 2011; Luo and Al-Dahhan, 2004; Yu et al., 2009). Light plays a significant role in the photoautotrophic cultivation of microalgae, and its availability in airlift bioreactors is influenced by the aeration rate, gas holdup, and the velocity of the liquid (Sanchez Miron et al., 1999; Li et al., 2011; Pruvost et al., 2006). In order to provide sufficient light for microalgae, it is necessary to design and optimize the internal structural parameters of the airlift bioreactor to improve mixing, light penetration, and gas injection (Degen et al., 2001; Barbosa et al., 2003; Vega-Estrada et al., 2005). In an airlift bioreactor with a concentric draught tube, the riser comprises the dark zone, and the downcomer comprises the photic zone (Barbosa et al., 2003). The light/dark cycle originates from the movement of the cells in and out of the photic zone, and the frequency of the light/dark cycle can significantly affect the efficiency of light utilization and algal growth and metabolism in airlift bioreactors (Vega-Estrada et al., 2005).

Abbreviations: A_d, cross-section area of the downcomer; A_r, cross-section area of the riser; P, cell density; V_g, gas holdup; h_0, clearance from the upper edge of the draft tube to the water level; h_1, clearance from the lower edge of the draft tube to the bottom of the reactor; t_c, cycle time; t_d, duration of the downcomer period; TKE, turbulence kinetic energy; ε, ratio between t_d and t_c; g, gravity acceleration; F, interfacial momentum exchange term; τ, viscous stress tensor; ρ, fluid density; α, volume fraction; t, flowing time of fluid; u, fluid velocity vector.

* Corresponding author. Tel./fax: +86 10 82622280.
E-mail address: czliu@home.ipe.ac.cn (C.-Z. Liu).

[1] These authors contribute equally to this work.

0960-8524/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.biortech.2012.05.123

Computational fluid dynamics (CFD) is a powerful tool that can be used to investigate multiple-phase flow. It has been used to aid in bioreactor design and process optimization for the culture of microorganisms, mammalian cells, and plant cells without having to perform numerous time-consuming bioreactor experiments. Recently, the hydrodynamic parameters of an airlift bioreactor with two different configurations were investigated using CFD simulation (Ebrahimifakhar et al., 2011). The successful application of the CFD method has also resulted in the design of several well-mixed bioreactors for microalgal cultivation and evaluating light absorption capacity in the bioreactors (Vega-Estrada et al., 2005; Perner et al., 2003; Sato et al., 2006). However, our understanding of the relationship among the inner structural parameters, multiphase fluid flow, and algal cultivation efficiency, is still limited.

The aim of the current work is to optimize the inner structure of a cylindrical airlift bioreactor using a two-dimensional axisymmetric CFD model. The goal is to design an effective mixing process to improve the growth of *Botryococcus braunii*, a slow-growing, green microalgae species with the ability to produce a large amount of hydrocarbons (up to 75% of its dry biomass). The CFD simulation results were confirmed experimentally by cultivating the microalgae in a 2 L airlift bioreactor as well as in a scaled-up 40 L airlift bioreactor.

2. Methods

2.1. Microalgae cultivation

B. braunii, stored at the Institute of Process Engineering in Chinese Academy of Sciences, was grown on modified Chu 13 medium (Largeau et al., 1980). Algal cells were cultured by continuously supplying CO_2-enriched air (1.0%, v/v) at an air flow rate of 0.1 v/v/m (air volume/culture volume/min). The initial biomass concentration was 0.2 g L^{-1}, and the microalgal cultures were incubated at 25 ± 1 °C under a light/dark cycle of 16/8 h with a light intensity of 35 μmol m^{-2} s^{-1}.

2.2. Cylindrical airlift bioreactor

2 and 40-L cylindrical airlift bioreactors were constructed from glass columns that contained vertical stainless steel cylinders as the draft tubes and air spargers (compressed stainless steel particles) underneath the bioreactors for air supply (Supplemental materials – Fig. 1) (Xu et al., 2011). There are three arms at the bottom and the surrounding wall of each stainless steel cylinder, respectively. These arms ensure the cylinder does not move from the center of the airlift bioreactor. The symbol, h_0, represents the clearance from the upper edge of the draft tube to the water level, and h_1 is the clearance from the low edge of the draft tube to the bottom of the reactor. A_r and A_d are the cross-sectional areas of the riser and the downcomer, respectively. The average diameter of the air bubbles released from the sparger was approximately 2.0 mm, and they were measured using the method described by Liu et al. (2011).

2.3. Simulation method of computational fluid dynamics (CFD)

The simulation of the structure geometry and the calculation of the flow fluid were carried out using the software GAMBIT/FLUENT. The bioreactor structure is axial symmetric, therefore, a two-dimensional axisymmetric model was utilized. A structured grid was implemented with a total number of 2774 cells within the 0.02 × 0.051 m computation domain (Fig. 1). The air–water system in the bioreactor was considered as a two-phase flow. The CFD calculation was based on the mass, momentum, and

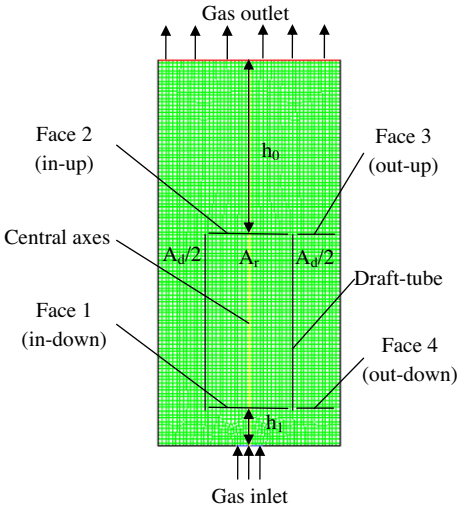

Fig. 1. Structured grid of the 2 L draft-tube airlift bioreactor (Reactor number: 1).

energy transfer. For this culture system, the working environment was at room temperature and little energy was transferred in this process. Therefore, the energy transfer process was ignored, and the governing equations for the gas–liquid system consisted of a set of continuity and momentum equations for each phase under the Euler–Euler multiphase model which is described as follows:

Continuous equation

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

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

Momentum transfer equation

$$\frac{\partial (\rho_i \vec{u_i} \alpha_i)}{\partial t} + \nabla \cdot (\alpha_i \rho_i \vec{u_i} \vec{u_i}) = -\alpha_i \nabla p + \nabla \cdot (\alpha_i \tau_i) + \nabla \cdot (\alpha_i \rho_i \vec{u'_i} \vec{u'_l}) + \rho_i \vec{g} \alpha_i \pm F_{ij} \tag{2}$$

where ρ is the fluid density, α is the volume fraction, t is the flowing time, u is the fluid velocity vector, g is the gravity acceleration, F is the interfacial momentum exchange term, and τ is the viscous stress tensor as described by Chen et al. (2005), and the subscript i and j represent the parameters in different phases.

The standard k–ε model was adopted to describe the turbulent flow behavior in the bioreactor. The details of the standard k–ε model are described in the FLUENT manual (ANSYS Inc., USA), in which turbulence kinetic energy is described as an important parameter in turbulent flow behavior.

Because the reactor receives surrounding light irradiance, the inner portion of the riser located in the middle of the reactor is defined as the dark zone and the downcomer close to the wall of the reactor is defined as the light zone. Gas holdup (V_g), turbulence kinetic energy (TKE), the ratio of the time period of the fluid in the downcomer (light zone) to the overall time period of a single cycle around the draft tube (ε), and the time period for the fluid to go around the draft tube one time (t_c) represent the mixing conditions in the reactor from diverse aspects, especially mixing in the irradiance direction. Particle tracking methods were employed to simulate the circulation process of the algae in the bioreactor. The tracer was set as a liquid with the same characteristics as water. The simulation step was described as follows: (1) hydrodynamics in the bioreactor were simulated until a steady-state was achieved; (2) tracer was injected into the bioreactor from the inlet with a certain flow velocity for several seconds; (3) after injection, the mass