Algal Research 8 (2015) 99–107

Contents lists available at ScienceDirect

Algal Research

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

Modelling light transmission, cyanobacterial growth kinetics and fluid dynamics in a laboratory scale multiphase photo-bioreactor for biological hydrogen production

Dongda Zhang, Pongsathorn Dechatiwongse, Klaus Hellgardt *

Department of Chemical Engineering, Imperial College London, United Kingdom

ARTICLE INFO

Article history:
Received 11 September 2014
Accepted 10 January 2015
Available online xxxx

Keywords:
Photo-bioreactor
CFD
Fluid dynamics
Light transmission
Cyanobacterial growth kinetics

ABSTRACT

An integrated reactor model was designed in this research to simulate fluid dynamics, local light intensity and the growth rate of nitrogen-fixing cyanobacterium *Cyanothece* sp. ATCC 51142 in a flat-plate photo-bioreactor by CFD technique. Previous research had already given the parameters in different algal growth kinetic equations. In this research, parameters were modified by CFD technique to improve the accuracy of cyanobacterial growth kinetic models. Finally, effects of recycling gas flow rate and geometry of sparger on local light intensity, growth rate, and fluid dynamics were analysed. Results show that recycling gas flow can increase liquid velocity and bubble volume fraction, however it prevents light transmission and the growth of cyanobacterium. Geometry of the sparger can affect liquid movement and distribution of both local light intensity and local growth rate.

1. Introduction

Electricity generation, natural gas processing, combustion of municipal solid wastes, and iron and steel manufacturing are some of the major contributors to current CO_2 emissions. These processes are believed to be the main reason for global warming, as they rely on the conversion of fossil carbon resources such as coal, petrol, and natural gas [16]. In order to fulfill the world's long-term energy demands and reduce CO_2 emissions, finding diverse and sustainable energy resources has become essential. Hydrogen has been proposed as one of the most sustainable fuels for the future. At present, industrial hydrogen production processes rely almost completely on the utilisation of fossil fuel based energy vectors, which are not renewable. It is therefore very attractive to find alternative means of producing hydrogen in an economic and environmentally friendly way.

One approach would be the production of bio-hydrogen by a microalgal photosynthetic process under anaerobic conditions that has attracted great interest since the middle of the twentieth century [9]. Bio-hydrogen production process simulations and economic efficiency calculations reveal that the most expensive part of the entire process is the anaerobic reactor, which requires more than 80% of the investment and makes this process uncompetitive with the current hydrogen production process [14]. Therefore, it is necessary to develop less expensive yet highly efficient anaerobic reactors. A detailed understanding and application of the fluid dynamics in photo-bioreactors are essential, not only to develop new types of reactors but to also decouple the intrinsic growth and production kinetics of the microalgae from fluid flow and light distribution limiting constraints.

In our study, the model microorganism is a unicellular nitrogen-fixing cyanobacterium *Cyanothece* sp. ATCC 51142, which is able to produce H_2 at the highest rate so far observed from wild-type as well as mutant microalgae [3]. Two O_2-sensitive biological enzymes – nitrogenase and bidirectional hydrogenase – are reported to facilitate the H_2 production activity of this cyanobacterium, with the former enzyme being generally dominant [18].

1.1. Photo-bioreactors

Numerous types of photo-bioreactors (PBRs) have been designed and modelled recently. Basically, PBRs can be divided into two types based on different cultivation methods. The first cultivation method is conducted in open pond systems. The second cultivation method is conducted in closed, transparent systems. PBRs based on this method are very popular and attractive due to the better control and higher production rates they offer. Various configurations are known such as bubble column PBR, airlift PBR, flat plate PBR, helical PBR, stirred tank PBR and internally-illuminated PBR. A discussion of the advantages and disadvantages of these different types of PBRs can be found in the corresponding literature [16,20,23,24].

Among the mentioned PBRs, the flat plate PBR seems to be advantageous due to its high surface-to-volume ratio, which can offer a better light distribution in the reactor. Light intensity is one key factor

* Corresponding author.
E-mail address: k.hellgardt@imperial.ac.uk (K. Hellgardt).

http://dx.doi.org/10.1016/j.algal.2015.01.006
2211-9264/

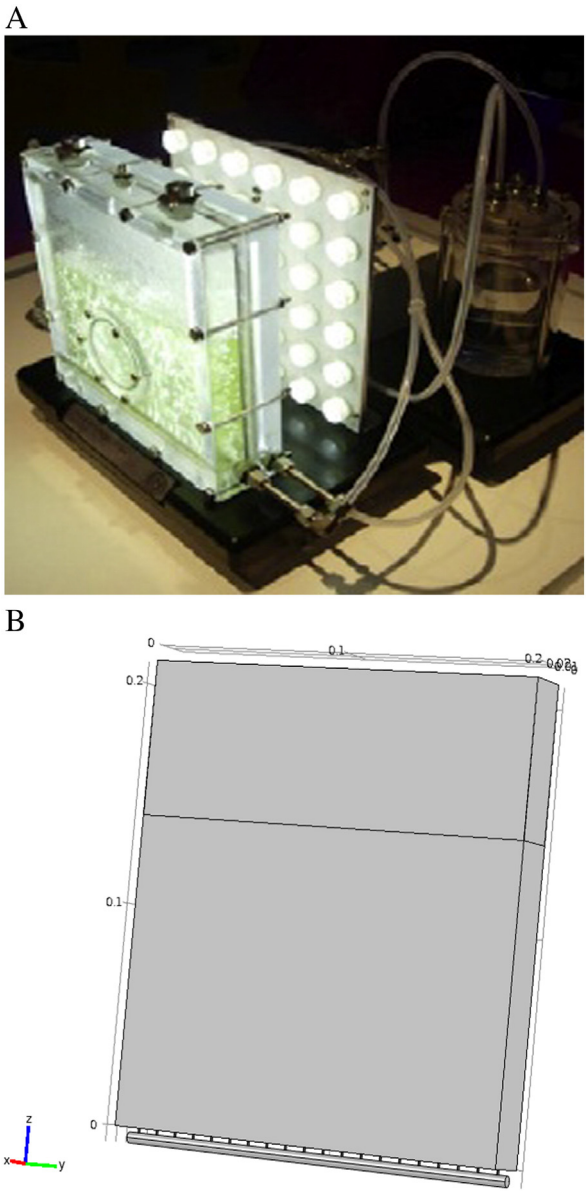

Fig. 1. Flat plate photo-bioreactor. A, profile of PBR. B, 3D model for simulation.

determining microalgal growth and hydrogen productivity. A flat plate photo-bioreactor thus forms the basis for the current analysis.

1.2. Laboratory photo-bioreactor

A novel flat plate photo-bioreactor (Fig. 1) was designed and operated for microalgal hydrogen production [20,22]. This reactor has the advantage of a high surface-to-volume ratio, which can offer a large illumination surface area. A dual-compartment reactor design was selected in order to ensure effective temperature control. The primary compartment is used to hold liquid culture and algae. It is this part where the growth and hydrogen production occurs. The secondary compartment has the function of regulating temperature in the primary compartment and acting as an IR filter for light passing into the primary compartment.

A re-circulating gas-lift system is used to provide gas mixture and agitation in the primary compartment. Gas is introduced into the PBR by a sparger in the bottom of the reactor. A bi-directional gas flow into the sparger is used to provide a uniform pressure distribution leading to an even gas-lift profile. Gas leaving the reactor is collected and re-introduced into the reactor by a gas re-circulating pump. Hydrogen measurement is accomplished by a MIMS (membrane inlet mass spectrometer) system. A LED array has the function of producing incident light.

This paper focuses on the primary compartment where the growth and hydrogen production occurs, the secondary compartment is not considered in the current model. The geometries of the primary compartment and sparger are given in Table 1A.

1.3. Objective and methodology

The performance of a PBR is the result of a complicated interplay of fluid dynamics, light transmission processes and cyanobacterial growth kinetics. This complexity makes it very difficult to analyse and decouple growth kinetics from extrinsic, reactor specific effects. Therefore, computational fluid dynamics (CFD) was used to model the sparger induced two-phase flow in the PBR and delineate the resulting light transmission processes in the reactor. This in turn allows proper determination of parameters involved in the description of different cyanobacterial growth kinetic models. It is then also possible to analyse the effects of recycle gas flow rate and geometry of the sparger on reactor performance.

Table 1
Geometry and boundary conditions of current photobioreactor.

(A) Geometry of primary compartment and sparger

Reactor	Compartment height, m	Compartment width, m	Compartment thickness, m	Liquid (culture) height, m	Membrane diameter, m
	0.2	0.2	0.025	0.14	0.05
Sparger	Diameter of holes, m	Distance of holes, m	Number of holes	Diameter of inlet, m	Length of sparger, m
	0.001	0.01	20	0.005	0.2

(B) Reactor model boundary conditions

	Gas phase	Liquid phase
Inlet conditions	Inlet velocity = 0.47 m/s (sparger)	Inlet velocity = 0
Outlet conditions	Gas outlet condition	$P = P_0$
Mass transfer	0	
Gravity force	$\mathbf{g} = (0,0,9.81)$	
Wall conditions	No gas flux at the boundary (reactor); non-slip model (sparger)	Velocity at the surface of wall is zero