Journal of Photochemistry and Photobiology B: Biology 131 (2014) 113–119

Contents lists available at ScienceDirect

Journal of Photochemistry and Photobiology B: Biology

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

Effects of mass transfer and light intensity on substrate biological degradation by immobilized photosynthetic bacteria within an annular fiber-illuminating biofilm reactor

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ARTICLE INFO

Article history:
Received 27 September 2013
Received in revised form 6 January 2014
Accepted 21 January 2014
Available online 30 January 2014

Keywords:
Photosynthetic bacteria
Cell-immobilized bioreactor
Substrate transport
Photo-biological reaction
Side-glowing optical fiber (SOF)

ABSTRACT

In this work, effects of mass transfer and light intensity on performance of substrate biodegradation by cell-immobilized photosynthetic bacteria were investigated within an annular fiber-illuminating bioreactor (AFIBR). In AFIBR, stable biofilm of photosynthetic bacteria was generated on the surface of side-glowing optical fiber to provide sufficient light supply and uniform light distribution in cell-immobilized zone for continuous substrate biodegradation during hydrogen production process. To optimize operation parameters for substrate degradation, a two-dimensional mass transfer model based on experimental data to describe coupled processes of substrate transfer and biodegradation in biofilm with substrate diffusion and convection in bulk flow region was proposed. Investigations on influences of substrate concentration, flow rate and light intensity were carried out. It was showed that the optimum operational parameters for the substrate degradation in the AFIBR are: 10 g/l substrate concentration, 100 ml/h flow rate and 3.1 W/m^2 light intensity.

1. Introduction

Photosynthetic bacteria (PSB) are widely distributed in environment and wastewater. They contain photosynthetic pigments: bacteriochlorophylls and carotenoids which can grow either in a phototrophic and a heterotrophic condition depending on the presence or absence of light. Beginning in the 1960s, scientists have studied the application of PSB in degrading organic pollutants in various wastewaters, such as, olive mill wastewater, soybean wastewater and diary wastewater [1,2]. Moreover, there is an increasing interest in PSB as candidates for bio-energy producer due to their capability of converting organic wastes to H_2. H_2 can be biologically produced from dark-fermentation or photo-fermentation processes. Dark-fermentation is a light-independent H_2 production process which can degrade organic substrates into volatile fatty acids. One of the deficiencies of dark-fermentation is insufficient degradation of the substrate. Since most anaerobic bacteria cannot utilize these acids as carbon sources. Therefore, not only are the organic acids from wastewater still left, but a much larger quantity of organic acids also accumulate during the dark-fermentation process. While photo-fermentation by PSB can furtherly use these short chain organic acids as electron donors for H_2 production with light energy, thus, has the advantage of further wastewater biodegradation in H_2 production [3,4]. But many factors, such as substrate concentration, flow rate and light intensity can influence these wastewater degradation processes. Thus, further investigations were needed to improve the performance of bioreactor.

Compared with traditional suspended growth bioreactors, cell-immobilized bioreactors have various advantages, such as easy operation in continuous flow, low cell losses, improved physical and chemical stability of biocatalyst, lower power requirements, and the ease with which the cells can be reused [5,6]. Therefore, increasing application of cell-immobilized systems has been found in the field of the wastewater degradation during biological H_2 production process. Two typical immobilized techniques, gel entrapment and biofilm, have been applied in practice. Compared with gel entrapment, biofilm is considered to be more suitable because of the advantages of sufficient light supply, preferential retention of active microbial mass, and high substrate conversion efficiency [7,8]. But, in the immobilized bioreactor, overall performance of the bioreactor was determined to processes of substrate transferred within fluid bulk zone and substrate transferred and

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http://dx.doi.org/10.1016/j.jphotobiol.2014.01.015
1011-1344/

Nomenclature

D	the effective diffusion coefficient of glucose in the bulk fluid, m^2/s	D_e	effective diffusion coefficient of glucose in the biofilm, m^2/s
C	glucose concentration in the bulk fluid, g/l	C_b	glucose concentration in the biofilm, g/l
C_i	glucose concentration at inlet of bioreactor, g/l	C_x	cell concentration in the biofilm, g/l
u	velocity in the bulk fluid zone, m/s	μ	the specific growth rate, l/s
L	length of the bioreactor, m	$Y_{x/s}$	the biomass yield
r_i	radius of the optical fiber, m	m	the maintenance coefficient of the PSB, l/s
L_f	biofilm thickness, μm	k_s	the Monod half-saturation constant, g/l
r_o	inner radius of the bioreactor, m	I	the light intensity at the surface of the optical fiber, W/m^2
u_{av}	average velocity in the bulk fluid zone, m/s		

biodegradation within biofilm. The system needs to be properly modeled to understand effects of mass transfer and photo-biological reaction.

Mathematical models for various configurations of the immobilized bioreactor, such as horizontal and vertical packed beds, fluidized beds, have been reported in the literatures [9,10]. Huang studied the mass transfer characteristics of the liquid film by taking into account the flow pattern and variation of liquid film thickness, but neglected substrate diffusion in fluid bulk zone [11,12]. Mowla established a diffusion–reaction model of biofilm, but they assumed substrate diffused only in the direction of the biofilm depth [13,14]. So far, few models have considered the effect of light intensity distribution within the biofilm.

In the present study, a two-dimensional steady state model is proposed to describe the substrate transfer and degradation within an annular fiber-illuminating biological H_2 reactor (AFIBR). In AFIBR, side-glowing optical fiber (SOF) is installed inside the reactor to offer a desired light intensity and uniform light distribution. The optical fiber also acts as an adhesion surface for PSB to form biofilm and realize continuous substrate degradation and H_2 production [15]. Substrate convection and diffusion in fluid bulk zone together with substrate diffusion and biodegradation in biofilm zone are considered simultaneously. Optimum operational parameters for the substrate degradation were thus obtained.

2. Materials and methods

2.1. Microorganism and medium

The strain used in this study was an indigenous photosynthetic bacterium cell isolated from silt sewage and was identified as Rhodopseudomonas palustris [8,18]. The bacterium grew in a synthetic medium using glucose as the sole carbon source. Experiments were conducted by using a basal medium: $K_2HPO_4{\cdot}3H_2O$ (1.006 g/l), KH_2PO_4 (0.544 g/l), $MgSO_4{\cdot}7H_2O$ (0.2 g/l), $FeSO_4{\cdot}7H_2O$ (0.0417 g/l), $C_5H_8NNaO_4$ (0.5 g/l), $C_6H_{12}O_6{\cdot}H_2O$ (10 g/l), NaCl (0.2 g/l), $CaCl_2$ (0.01 g/l), $(NH_4)_6Mo_7O_{24}{\cdot}4H_2O$ (0.001 g/l), $ZnSO_4{\cdot}7H_2O$ (0.001 g/l), H_2NCONH_2 (1.677 g/l), yeast extract (1.0 g/l), growth factor solution (1 ml/l). Elements in growth factor solution were: thiamin hydrochloride (1.0 g/l), riboflavin (1.0 g/l), nicotinic acid (1.0 g/l), biotin (1.0 g/l).

2.2. Analytical methods

An electronic analytical balance was used to determine the quantity of elements in the basal medium. The illumination intensity was measured with a PAR quantum sensor (USA, SA-190). The concentration of the carbon source (glucose) was measured by the 3, 5-dinitrosalicylic acid method. The dry weight of biomass within bioreactor was calculated from OD600 values using a standard method [8,18]. The performance of substrate degradation in the AFIBR can be evaluated by substrate consumption rate (SCR) and substrate degradation efficiency (SDE) with their definitions as following:

$$\mathrm{SCR(mmol/g\ dry\ cell/h)} = \frac{\text{Amount of substrate consumed (mmol)}}{\text{Substrate consumption time (h)} \times \text{dry cell weight (g)}} \quad (1)$$

$$\mathrm{SDE}\ (\%) = \frac{\text{Amount of substrate consumed (mol)}}{\text{Amount of substrate provided (mol)}} \times 100\% \quad (2)$$

3. Model description

The scheme of the annular fiber-illuminating biological H_2 reactor (AFIBR) is shown in Fig. 1. The reactor is a sealed cylinder with 50 mm diameter and 300 mm length, and a side-glowing optical fiber (SOF) with 18 mm diameter in the axial direction. Meanwhile, stable biofilm with a thickness of L_f covers on the optical fiber surface. The inlet for substrate solution is set at one end of the AFIBR and the outlet at the other end. The substrate solution is continuously introduced to form an axial flow through the AFIBR in velocity u, and the produced H_2 flows out with the solution for separation. Thus, the AFIBR can be generically described as a system with two separated zone: the biofilm zone and the bulk fluid zone. Owing to the concentration-diffusion and convection–diffusion, the substrate in the solution transfers into the biofilm zone along the radial direction to satisfy the degradation of PSB, leading to axial variation of the substrate concentration in the bulk fluid zone. Therefore, a two-dimensional steady-state mass transfer model is proposed for the AFIBR based on above understanding.

3.1. Assumptions

Following assumptions are set for the two-dimensional simulation on the substrate transfer and biodegradation in a steady and continual operation AFIBR.

(1) The biofilm is uniformly distributed along the optical fiber and its properties, i.e. thickness, density and specific surface area, are constant.
(2) The substrate, glucose, diffuses both in the thickness direction of the biofilm and in the axial direction of the reactor. The axial flow of the substrate inside the biofilm is ignored.
(3) The light intensity inside the biofilm is the same as that on the surface of the optical fiber because of the teeny thickness of biofilm compared to the size of optical fiber.
(4) The cell growth and substrate utilization kinetics obtained from suspended cell culture are still available to the biofilm on the optical fiber.
(5) The fluid flow inside the AFIBR is fully developed and no disturbance and back mixing happen.