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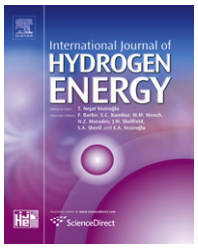

A feasibility study on unsaturated flow bioreactor using optical fiber illumination for photo-hydrogen production

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ABSTRACT

An unsaturated flow bioreactor with *Rhodopseudomonas palustris* CQK 01 was developed for photo-hydrogen production. The bioreactor developed in this work consisted of a reaction bed packed with spherical glass beads and internal optical fiber that provided uniform light distribution and achieved high light transmission efficiency. Unsaturated conditions were obtained by filling both argon and nutrient solution into the bioreactor. Experimental results demonstrated the feasibility of the biofilm formation in an unsaturated environment. With the formed biofilm, parametric studies on the photo-hydrogen production performance under different liquid flow rates and initial substrate concentrations were conducted. It was found that the performance of the bioreactor came to the optimal state at the liquid flow rate of 500 mL/h. Moreover, such a design enabled the bioreactor to be operated at relatively high glucose concentration without the substrate inhibition, yielding a good biohydrogen production performance.

1. Introduction

Photosynthetic bacteria (PSB) is considered as the most promising candidate for large-scale hydrogen production owing to the advantages of its high theoretical conversion yield and capability of using a variety of organic substrates derived from waste treatment processes [1,2]. However, it should be pointed out that the hydrogen production performance with PSB is still relatively poor due to the low cell concentration and light energy utilization caused by the shielding effects [3–6]. One of the solutions to these problems for the improvement in the photo-hydrogen production performance can be the optimization of the bioreactor design. As a result, many researchers all over the world have turned their focus on this area.

In general, available bioreactors can be divided into two types: suspended-cell bioreactor and immobilized-cell bioreactor. Suspended-cell bioreactors, such as continuously stirred tank reactor (CSTR), are widely adopted for the photo-hydrogen production because of their simple operation and good mass transfer [7,8]. Nevertheless, such a design has difficulties in intensification of the cell concentration, and efficient solid–liquid separation and avoidance of cell washout to maintain stable operation are hard to overcome as a result of its intrinsic characteristics [9]. Immobilized bioreactors, including biofilm and cell entrapment techniques, are

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feasible technique, which can not only increase cell concentration and operation stability, but also improve the volumetric productivity and shorten the hydraulic retention time (HRT) [10,11]. Besides, it can also enhance the ability to recover and reuse the cell mass [12]. In immobilized-cell bioreactors, biofilm-based bioreactor seems to be a more reasonable mean because of high mass transfer rate, strong mechanical strength and good stability for long-term operation [13,14]. At present, the biofilm-based photo-hydrogen production was mainly used in saturated flow type of bioreactor [5,11], but the biogas collection from the liquid phase is limited, resulting in a negative effect on the performance of photo-hydrogen production. Note that in biological hydrogen production systems, the limitation of biogas collection can be avoided by using an unsaturated flow type of bioreactor, such as trickling biofilter, because it can promote the rate of gas transfer in the biofilm due to the thin liquid film over the biofilm when medium solution is applied over the support matrix [15–17]. In addition, unsaturated flow bioreactors are easy to achieve high substrate transfer rate and efficient gas-liquid separation [18]. In recent years, unsaturated flow bioreactors have been studied for the biohydrogen production by dark fermentation [15–19]. Photo-hydrogen production with unsaturated flow bioreactor has not yet been reported.

In this study, an unsaturated flow bioreactor was developed for photo-hydrogen production using PSB. An optical fiber was used as an internal light source that obtained uniform light distribution with a high relative ratio of illumination surface area to bioreactor volume as well as high light transmission efficiency without heat generation [14,20–22]. The objective of this research was to demonstrate the feasibility of biofilm formation in an unsaturated environment, following the surface morphology of the biofilm was characterized. Meanwhile, the effects of different operating conditions, including the liquid flow rate and initial substrate concentration, on the photo-hydrogen production performance were also investigated.

2. Materials and methods

2.1. Microorganism and medium

In this study, *Rhodopseudomonas palustris* CQK 01 used for photo-hydrogen production was isolated from the municipal sewage sludge by repetitious purification. The isolated cells were then cultivated in a synthetic medium referring to literature [14]. In pre-culture, the sole carbon source of glucose with an initial concentration of 50 mM was utilized. The cells inoculated to the bioreactor were cultivated anaerobically at 30 °C for 72 h under the anaerobic atmosphere created by argon and an illumination intensity of approximately 4000 lux (illuminated by tungsten filament lamp).

2.2. Unsaturated flow bioreactor design and operation

The unsaturated flow bioreactor developed in this work was sketched in Fig. 1. The bioreactor was a sealed vessel (200 mm in height, 50 mm in diameter) fabricated by polymethyl methacrylate (PMMA) and packed with spherical glass beads (4 ± 0.5 mm in diameter). A side-light plastic-clad optical fiber (diameter: 18 mm, working length: 200 mm; Guangzhou, China) protected by a PMMA tube was immersed into the bioreactor as light source to enable the uniform light distribution. Before experiment, the protective cladding was removed and the optical fiber was polished until the desired light intensity of ca. 30 W/m^2 was obtained.

The experiments consisted of two stages: the start-up stage and performance testing stage. In the start-up stage, 200 mL medium with 10% inoculum and a certain amount of argon gas were first filled into the bioreactor to create an unsaturated and anaerobic environment. The medium with the volumetric flow rate of 500 mL/h was then recycled by a peristaltic pump until a stable biofilm of the PSB was formed on the surface of spherical glass bead. Moreover, 50-mL medium was discharged and 50-mL fresh nutrient medium of 30 mM was daily compensated into the bioreactor to avoid nutrition-competition by suspended cells and to provide microorganism with nutrients for the formation of biofilm. In the wake of the start-up, the performance testing was conducted in a closed loop system and 200-mL fresh nutrient medium along with argon was fed into the bioreactor to create an unsaturated and anaerobic condition.

2.3. Estimation of photo-hydrogen production performance

The photo-hydrogen production performance of the unsaturated flow bioreactor was assessed by cumulative hydrogen production (CHP), transient hydrogen production rate (THPR), medium pH value, substrate concentration (SC), substrate degradation efficiency (SDE) and overall light conversion efficiency (OLCE).

$$\mathrm{THPR\ (mmol/L/h)} = \frac{\Delta \mathrm{CHP\ (mmol)}}{\Delta T\ \mathrm{(h)} \times \mathrm{bioreactor\ volume(L)}}$$

where ΔCHP and ΔT represent the increments of cumulative hydrogen production and hydrogen evolution time, respectively.

$$\mathrm{SDE\ (\%)} = \frac{C_0\ \mathrm{(mM)} - C_n\mathrm{(mM)}}{C_0\ \mathrm{(mM)}}$$

with C_0 and C_n representing the substrate concentrations at the initial time and sampling time, respectively.

$$\mathrm{OLCE\ (\%)} = \frac{\mathrm{H_2\ output\ (g)} \times \mathrm{H_2\ energy\ content\ (J/g)}}{\mathrm{light\ energy\ input\ (J)}} \times 100 = \frac{0.067 \times CHP\mathrm{(mmol)}}{I\ \mathrm{(W/m^2)} \times A\ \mathrm{(m^2)} \times t_n\ \mathrm{(h)}} \times 100$$

where I is the light intensity, A the irradiated area, and t_n the time interval of photo-hydrogen production from the beginning to the sampling time.

2.4. Analytical method

Hydrogen in the biogas was analyzed by gas chromatograph (SC-3000, Chongqing, China) using a thermal conductivity detector (TCD) and a 2 m stainless-steel column packed with porous styrene particles. Argon was used as the carrier gas with a flow rate of 25 ml/min. The temperatures of the gas