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Power generation in fed-batch and continuous up-flow microbial fuel cell from synthetic wastewater

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ABSTRACT

Up-flow bioreactors have the advantages of retaining very high cell density and having high mass transfer efficiency. The recirculation rate could improve the up-flow rate in up-flow bioreactor. A two-chamber UFMFC (up-flow microbial fuel cell) is constructed with flat graphite electrodes and anion exchange membrane for electricity generation. The anode chamber is seeded with compost culture enriched on xylose and operated on synthetic wastewater with 0.5 g/L xylose, external resistance of 100 Ω, at pH 7.0 and 37 °C in fed-batch mode. The cathode chamber in the top of the UFMFC is filled with potassium ferricyanide (pH 7.0) as the electron acceptor. The effects of different recirculation rates of 1.2, 2.4, 4.8 and 7.2 RV (reactor-volumes)/h to increase the mass transfer and electricity production are determined in fed-batch mode. At a recirculation rate of 4.8 RV/h, a power density of 356 ± 24 mW/m^2 with CE (coulombic efficiency) of 21.3 ± 1.0% is obtained. Decreasing HRT (hydraulic retention time) could improve the electricity production performance of UFMFC in continuous mode. The power generation is increased to 372 ± 20 mW/m^2, while CE remains at 13.4 ± 0.5% with HRT of 1.7 d and optimum recirculation rate of 4.8 RV/h on continuous mode. Microbial communities were characterized with PCR (polymerase chain reaction) – DGGE (denaturing gradient gel electrophoresis). In the end of the experiment, the biofilm contained both fermenting and exoelectrogenic bacteria, while fermenting and nitrate-reducing bacteria were mainly present in the anodic solutions. Moreover, some changes occurred in the microbial communities of the anodic solutions when the MFCs were switched from fed-batch to continuous mode, while the differences were minor between different recirculation rates in fed-batch mode.

1. Introduction

Using biotechnology to obtain bioenergy, such as hydrogen, methane, butanol and electricity from wastes or wastewaters is a promising way of generating renewable energy. Bioelectricity could be generated sustainably in MFC (microbial fuel cells) during wastewater treatment [1–3]. In MFC, microbes convert the chemical energy stored in organic compounds into electricity [4]. This approach has dual advantages of simultaneously reducing wastewater pollution and producing bioenergy. The electricity generation efficiency is affected by MFC architecture, electrode design and exoelectrogenic cultures [5].

Many types of architectures, such as micro-size MFC [6], vertical MFC using up-flow feeding [7–9] or down-flow feeding [10], baffled stacking MFC [11], and tubular MFC [12], have been used to enhance the efficiency of electricity generation. UASB (up-flow anaerobic sludge blanket) bioreactor has been used extensively for treatment of organic wastes to biogas. UASBs have the advantages of retaining very high cell density and having high mass transfer efficiency [13]. UASB-MFCs have been applied for treatment of sucrose wastewater [7], sulfate wastewater [14] and landfill leachate [15] in batch, fed-batch and continuous modes. Effluent recirculation has been shown to enhance the contact between microorganisms and substrate as well as lower the residual organic fraction of effluent [16]. Effluent recirculation is widely used in anaerobic UASB reactor [17], anaerobic fluidized bed reactor [18], anaerobic baffled reactor [19] and two-phase reactor system [20].

Losses in microbial fuel cells can be related to activation, ohmic and mass transport losses. Ohmic losses are related to electron and proton flows through the electrodes, electrolytes and

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Nomenclature

A	the surface area of the anode electrode (m^2)
CE	coulombic efficiency (%)
DGGE	denaturing gradient gel electrophoresis
GC	gas chromatography
HRT	hydraulic retention time (d)
I/A	current density (A/m^2)
I	current (A)
P/A	power density (W/m^2)
P	power (W)
PCR	polymerase chain reaction
R	fixed external resistance (Ω)
RV	reactor-volumes
UASB	up-flow anaerobic sludge blanket
UFMFC	up-flow microbial fuel cell
V	voltage

interconnections [21,22]. Activation losses are dominant at lower current densities, while mass transport losses become more important at higher current densities. Mass transport losses are caused by substrate diffusion or product removal close to the electrodes [21]. Thus, increasing recirculation rates and flow rates close to the anode electrode can be hypothesized to decrease the anodic mass transport losses [5].

This study investigated the electricity generation efficiency of an up-flow two-chamber MFC in fed batch and continuous modes. Synthetic wastewater with xylose, an important constituent of lignocellulosic material, was used as substrate and mixed exoelectrogenic culture enriched from compost as inoculum. It was hypothesized that increasing recirculation rates would increase the mass transfer and electricity yields. Thus, the effects of recirculation rates on electricity production, xylose degradation and microbial community compositions were determined.

2. Experimental

2.1. Inoculum preparation

An exoelectrogenic culture enriched from compost sample [23] in two-chamber MFCs with fed-batch operation was used as inoculum. The culture was grown in two-chamber cubic MFCs with plain graphite electrodes (total surface area of the anode electrode 38.5 cm^2), cation exchange membrane (CMI-7000) and external resistance of 100 Ω. A synthetic growth medium [23] with 1 g/L xylose, at pH 7 and 37 °C were used. The culture performance was as follows; maximum voltage, PD (power density) and CE (coulombic efficiency) were 476 mV, 30 W/m^2 and 82%, respectively [23].

2.2. MFC configuration and experimental conditions

The vertical two-chamber up-flow MFC (UFMFC, Fig. 1) consisted of two polycarbonate or poly (methyl methacrylate) halves separated by an Ultrex anion exchange membrane (AMI-7000, Membranes International, Ringwood, NJ). The working volumes of anode and cathode were 500 mL and 300 mL respectively. Graphite plate electrodes (4.6 × 2.7 × 0.6 cm, 38.5 cm^2, McMaster-Carr, Aurora, OH) were used in both chambers and were pretreated as described by Bond and Lovley [24] prior to use. The same medium used to enrich the compost culture with 0.5 g/L xylose was used as the synthetic wastewater in the anode. Potassium ferricyanide (50 mM $K_3Fe(CN)_6$) in phosphate buffer (100 mM Na_2HPO_4, pH 7.0) was used as catholyte.

The MFC was inoculated (10%, v/v) with the enrichment culture and operated at 37 °C in fed-batch mode. Recirculation rates of 1.2, 2.4, 4.8 and 7.2 RV (reactor-volume)/h were tested between days 1 and 107. On day 108, the feeding was switched to continuous mode with optimized recirculation rate of 4.8 RV/h. In continuous mode, HRT (hydraulic retention time) of 3.7 and 1.7 d were tested. During each feeding, catholyte was replaced by fresh $K_3Fe(CN)_6$, 50 mL sample was taken from the anolyte and the sample volume was replaced with fresh medium and feed (final xylose concentration 0.5 g/L). A fixed external resistance (R) of 100 Ω was connected between the electrodes and the closed circuit potential of the MFC was recorded every 2 min with an Agilent 34970A data logger. The power density was calculated according to the following equation:

$$P/A = I \times V/A \quad (1)$$

where *V* is voltage (V), *I* ($I = V/R$) the current (A), and *A* the surface area of the anode electrode (m^2).

CE was defined as the ratio of total coulombs transferred to the anode from xylose to the maximum possible coulombs present in removed substrate [11]. Mean values of CE, *I*, *P*, *I/A* and *P/A* were calculated at each operating condition. Polarization characteristics of the MFCs were determined by decreasing the resistance (from 1 M Ω to 5 Ω) stepwise in 5 min intervals by using a resistance substitution box. The internal resistances of the MFCs were calculated by the polarization slope method [5].

2.3. Analytical methods

APHA Standard Methods [25] was used to determine pH. Concentrations of alcohols (ethanol and butanol) and volatile fatty acids (VFA, including acetate, propionate, butyrate, isobutyrate and valerate) were analyzed using a gas chromatography equipped with a flame ionization detector (Perkin Elmer Clarus 500 GC) and HP-5MS column. The temperatures of injector and detector were 250 and 280 °C, respectively. Oven temperature was held at 50 °C for 3 min, increased from 50 to 100 °C at the rate of 20 °C/min, from 100 to 150 °C at 10 °C/min and finally held at 150 °C for 5 min. Gas formation in the anode was measured by connecting tedlar bags (Zefon International, Ocala, FL) to the anode chamber.

2.4. Bacterial community profiling

Bacterial community samples were taken from the anode solution before each operational change and from the biofilm in the end of the experiment. Bacterial communities of anode solution and biofilm were analyzed by using DNA extraction, PCR (polymerase chain reaction) – DGGE (denaturing gradient gel electrophoresis) of partial 16S rRNA genes followed by gene sequencing as described earlier by Mäkinen et al. [23]. Sequence data were analyzed with Bioedit-software (version 7.0.5.3) and compared with sequences in GenBank (http://blast.ncbi.nlm.nih.gov/Blast.cgi).

3. Results and discussion

3.1. Effect of recirculation rate in fed-batch mode on electricity generation and soluble metabolic products

Table 1 shows the effects of recirculation rates on the CE, current, current density and power density in fed-batch mode. Increasing the recirculation rate from 1.2 to 4.8 RV/h enhanced the