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Effects of hydraulic pressure on the performance of single chamber air-cathode microbial fuel cells

Shaoan Cheng*, Weifeng Liu, Jian Guo, Dan Sun, Bin Pan, Yaoli Ye, Weijun Ding, Haobin Huang, Fujian Li

State Key Laboratory of Clean Energy, Department of Energy Engineering, Zhejiang University, Hangzhou 310027, PR China

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ABSTRACT

Scaling up of microbial fuel cells (MFCs) without losing power density requires a thorough understanding of the effect of hydraulic pressure on MFC performance. In this work, the performance of an activated carbon air-cathode MFC was evaluated under different hydraulic pressures. The MFC under 100 mmH_2O hydraulic pressure produced a maximum power density of 1260 ± 24 mW m^{-2}, while the power density decreased by 24.4% and 44.7% as the hydraulic pressure increased to 500 mmH_2O and 2000 mmH_2O, respectively. Notably, the performance of both the anode and the cathode had decreased under high hydraulic pressures. Electrochemical impedance spectroscopy tests of the cathode indicated that both charge transfer resistance and diffusion transfer resistance increased with the increase in hydraulic pressure. Denaturing gradient gel electrophoresis of PCR-amplified partial 16S rRNA genes demonstrated that the similarity among anodic biofilm communities under different hydraulic pressures was $\geq 90\%$, and the communities of all MFCs were dominated by *Geobacter* sp. These results suggested that the reduction in power output of the single chamber air-cathode MFC under high hydraulic pressures can be attributed to water flooding of the cathode and suppression the metabolism of anodic exoelectrogenic bacteria.

1. Introduction

The threats posed by the impending exhaustion of fossil fuels and continuing trends of global warming warrant speedy development of sustainable energy technologies. Microbial fuel cell (MFC) is an emerging renewable bioenergy technique in which electrical current is generated from organic wastes using bacteria as catalysts (Allen and Bennetto 1993; Cheng et al., 2006; Lovley 2008; Rabaey and Verstraete 2005; Zhang et al., 2010). There are several types of MFCs depending on their use of two-chamber (Kim et al., 2005), single-chamber (Cheng et al., 2006), up-flow (He et al., 2006), flat (Min and Logan, 2004) or tubular (Zuo et al., 2007) devices. Because of their high power output, simple structure and low cost, single-chamber air-cathode MFCs hold great promise for large scale applications in wastewater treatment (Logan et al., 2006; Logan, 2004). In the past few decades, the power output of MFCs has increased gradually at the laboratory scale (reactor size of milliliters). The maximum power density of MFCs currently reported is 2.87 kW m^{-3}, which was achieved in an air-cathode MFC with reactor size of 30 mL (Fan et al., 2012). This indicates that the MFC technology could be competitive with traditional anaerobic digestion in terms of power density.

For practical application and commercialization in wastewater treatment or biogas production, MFCs must be scaled up. However, the volumetric power densities were found to be almost 2–4 orders of magnitude lower than laboratory-scale MFCs when the MFC size was scaled up to several liters or more (Cheng and Logan, 2011; Clauwaert et al., 2009; Liu et al., 2008; Logan, 2010). Factors such as electrode spacing, electrode specific surface area and hydraulic pressure change as MFCs are scaled up and may account for the observed decrease in power density. It has been proposed that one of the main reasons for power loss upon scaling up of MFCs is the increase in internal resistance (Clauwaert et al., 2008). Internal resistance can be reduced by decreasing the electrode spacing or increasing the solution conductivity (Liu et al., 2008). Cheng and Logan (2011) proposed that cathode specific surface area could be another critical factor since the volumetric power density of MFC is linearly related to the cathode specific surface area. In large sized MFCs, an electrode may experience quite different hydraulic pressures at different water logging depths. For instance, the bottom of an upright electrode of 1 m height could experience 98 kPa higher hydraulic pressure than the top area. High hydraulic pressure may influence the catalytic activity of cathodes and the metabolism of exoelectrogenic bacteria

* Corresponding author. Tel.: +86 571 87952038; fax: +86 571 87951616.
E-mail address: shaoancheng@zju.edu.cn (S. Cheng).

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in anodes. Thus, managing hydraulic pressure could be crucial for the performance of large-scale MFCs. However, little is known about the effect of hydraulic pressure on the performance of MFCs.

In this study, the performance of a single-chamber air-cathode MFC under different hydraulic pressures (100–2000 mmH_2O) was examined. The effects of hydraulic pressure on electrode performance were analyzed by polarization measurement, electrochemical impedance spectroscopy (EIS) and polymerase chain reaction denaturing gradient gel electrophoresis (PCR-DGGE) followed by sequencing of partial 16S rRNA genes.

2. Experimental methods

2.1. MFC configuration and operation

Single-chamber cubic-shaped base MFC with electrode spacing of 1.2 cm was constructed as previously described (Logan, 2004). The MFC used in this study was constructed by assembling a Polyvinyl Chloride (PVC) tube (2.5 cm in inner diameter) of various heights on the top of the base MFC (Fig. 1). Air-cathode (projected area 7 cm^2) was made of nickel foam containing an activated carbon catalyst (6 mg cm^{-2}) and four PTFE diffusion layers (Cheng and Wu, 2013). The cathode was placed at the bottom of the reactor. A graphite brush anode (2 cm in diameter and 2.5 cm in length; Hangzhou Jinsheng brush factory, China) was inserted 1.2 cm above the cathode. A glass fiber mat (2 mm thick) was placed on the water-facing side of the cathode to prevent short circuit of the electrodes. Hydraulic pressure on the electrodes was controlled by varying the length of PVC tube which was filled with nutrient electrolyte. Five hydraulic pressures of 100 mmH_2O, 500 mmH_2O, 1000 mmH_2O, 1500 mmH_2O, and 2000 mmH_2O were studied in this work. The upper end of the PVC tube was fully sealed to minimize oxygen diffusion from the atmosphere to the anode.

The MFCs were inoculated with a mixture (1:1 in volume) of inoculum and nutrient medium. The inoculum was the effluent of an MFC that had been operated for approximately two years. The nutrient medium consisted of 1 g L^{-1} sodium acetate and 50 mM phosphorus buffer solution (PBS; $Na_2HPO_4 \cdot 12H_2O$, 11.466 g L^{-1}; $NaH_2PO_4 \cdot 2H_2O$, 2.75 g L^{-1}; KCl, 0.31 g L^{-1}; NH_4Cl, 0.13 g L^{-1}; and trace minerals 12.5 mL L^{-1}). After one cycle of inoculation, the MFCs were operated in nutrient medium on a fed-batch mode at an external resistance of 1000 Ω. All the tests were conducted in duplicate in a temperature-controlled room at 30 °C.

2.2. Measurements and calculations

The voltage (U) across the external resistor was measured at 20 min intervals using a data acquisition system (2700, Keithley Instrument Inc., USA). Current (I) and power (P) densities normalized by the projected surface area of the cathode (7 cm^2) were calculated as previously described (Kim et al., 2005). The maximum power density of MFCs was obtained by the polarization curve. The polarization curve was determined by varying the external resistance from 1000 Ω to 20 Ω in a decreasing order, with a polarization time of 20 min for each resistance value. In order to minimize the effect of different electrolyte volumes on power output, the power density curves were measured in the stable stage of each MFC, i.e. when the substrate was sufficient and voltage output kept stable.

The electrochemical character of the cathode under different hydraulic pressures was monitored by electrochemical impedance spectroscopy (EIS). EIS tests were performed on a potentiostat (CompactStat.e, Ivium Technologies B.V., Netherlands) using an electrochemical cell consisting of a working electrode (cathode of 7 cm^2 projected surface area), an Ag/AgCl reference electrode and a Pt counter electrode. Impedance measurements were conducted under both open circuit potential (OCP) and polarized conditions of −015 V and 0 V (vs Ag/AgCl) over a frequency range of 100 kHz to 1 mHz with a sinusoidal perturbation of 10 mV amplitude. The spectra were fitted with data obtained from an equivalent circuit consisting of a solution resistance, a charge transfer element and a diffusion element (Zhang et al., 2011).

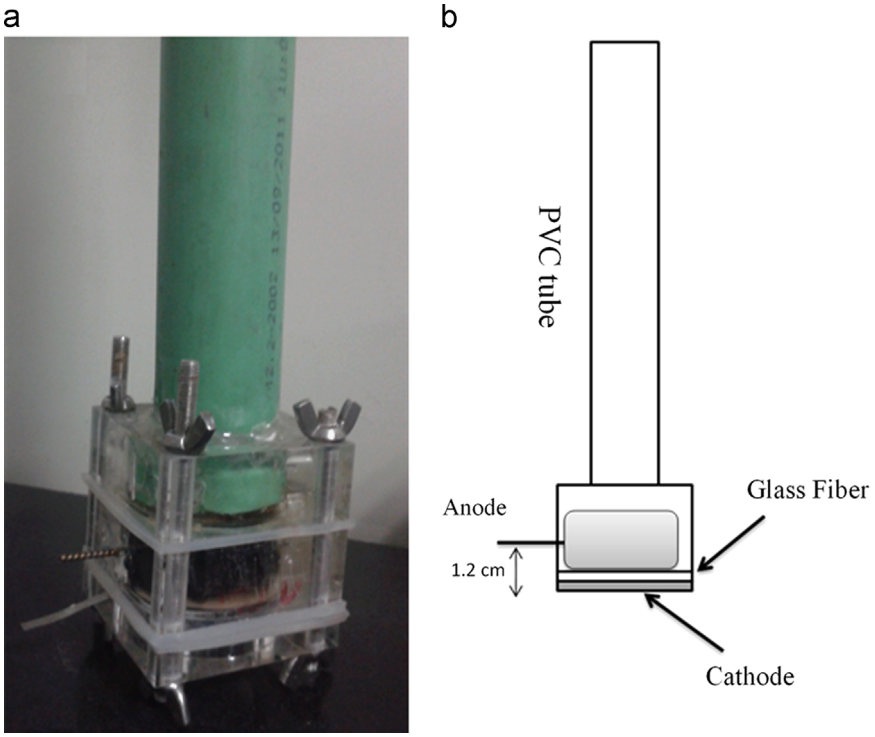

Fig. 1. Photograph of the experimental MFC (a) and schematic illustration of its design (b).