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Performance of freshwater sediment microbial fuel cells: Consistency

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ABSTRACT

This study experimentally examined the performance consistency of sediment microbial fuel cells (SMFCs) with the same geometry and the same startup protocol. The cells revealed very different characteristics after startup. Doubling the anodic surface area did not enhance the cell performance. Stirring the sediment and aerating the upper water increased voltage output, and the chemical environments (pH and dissolve oxygen concentrations) effectively supported the operation of the studied SMFC. However, individual anodic biofilms and their functions are highly sensitive to extremely small changes in the local environment. The highly inconsistent function of anodic biofilms in SMFCs may hinder their widespread adoption.

Introduction

Microbial fuel cells (MFCs) convert electron donors on the anode to their oxidized form with the released electrons being transferred over an external loading to cathode [1–6]. Relevant review articles with more than 700 citations are available [7–10]. Sediment microbial fuel cells (SMFCs) are a modification of the MFC. The anode is embedded in an anaerobic sediment and cathode was placed at the upper, aerobic water with the electron donors in the sediment as the fuel [11–13]. Since SMFCs generally have low power levels [14,15], they have been proposed for use in sub-water sensors or as (long-term) bioremediation devices for polluted sediments [16–18].

When numerous lab-scale MFCs are started up using an identical protocol, cell performance is generally uncorrelated. Weng and Lee [19] started up four identical sulfate-reducing bacteria-MFCs using abiotic cathodes to measure the consistency of cell performance when using sulfate and citrate-containing water. Because of the large variation in cell performance, these authors proposed that local environment in cell compartments significantly affected the cell performance.

Consistent cell performance is the prerequisite for field application of SMFCs. This study examined the performance

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consistency of SMFCs that had an identical geometry and were started up using an identical protocol. The effects of anodic surface are, mass transfer resistances in matrixes were studied and discussed.

Material and methods

Sediment and SMFC

Eight identical 1-L containers were used as the reactor compartments. In each SMFC, both the anode and cathode were composed of carbon cloth (5 cm × 5 cm; W0S1002; CeTech Co., Taichung, Taiwan). The cathode was embedded with 1 mg cm^{-2} Pt catalyst.

The sediment samples were collected from Drunken Moon Lake of National Taiwan University main campus (25 1′7″N 121 32′31″E). The samples were filtered through 5-mm coarse screens to remove most grit and sand. After filtration, the samples had an approximately neutral pH at room temperature (approximately 24 °C). The sediment was added to the 1-L containers to form 10-cm bottom layers. The lake water collected from the same site formed the 10-cm thick upper supernatant layer. In batch 1 tests, eight SMFCs were started up: group A (×2) with one abiotic anode and one cathode, group B (×2) with one biotic anode (discussed later) and one cathode, group C (×2) with two biotic anodes in series and one cathode, and group D (×2) with two abiotic anodes in series and one cathode. In all batch 1 tests, the anodes and cathodes were placed 5 cm below and 5 cm above the sediment–supernatant interface, respectively. The biotic anodes were cultivated in another MFC that had been used continuously for 3 months to treat municipal wastewater.

After the 64-d tests, the sediment of one of the two group A cells was stirred at 1 rpm for 1 h to enhance the supply of substrates to the anodes. After stirring, the upper water layers of both of the tested SMFCs were aerated by air at a flow rate of 0.5 L/min beginning at 930 h.

In the batch 2 test, eight identical anodes were placed at 5 cm below the water–sediment interface of an SMFC in group A, but the volume was increased to 2L. The startup protocol was the same as that in the batch 1 tests. The cell performances of these cells were monitored to measure the consistency of cell performance.

Measurements and analyses

The voltage drop over an external load of 1000 Ω in each MFC was recorded at 180 s intervals using a data acquisition system (Advantech Co., Taipei, Taiwan). Cyclic voltammetry (CV) of each tested SMFC was conducted using an electrochemical workstation (model CHI611, CH Instruments, Inc. Austin, TX, USA). The working electrode of a potentialstat (LPS 505N, Motech Industries, Inc., Taipei, Taiwan) was connected to the anode to control its local potential, and an Ag/AgCl electrode was used as the reference electrode. The CV tests of the anode were conducted from −0.6 to +1.0 V.

A pH meter (pHS-25, Shanghai, China) was used to measure the pH of sediment suspension. The dissolved oxygen (DO) content was measured by a Multi 340i-WTW (Geotech Environmental Equipment Inc., Denver) [20–22].

Results and discussion

Reactor performance: batch 1

Fig. 1 shows the voltage data for eight SMFCs during and after startup. In terms of voltage from highest to lowest, the order was group B > group C > group A > group D. For group B, the maximum voltage reached >200 mV. The corresponding maximum voltage for group C was 100–120 mV. The group D cells showed a rapid voltage drop 1 day after startup. In group A, the voltage output (40–80 mV) was stable during the 64-d testing period. Fig. S2 shows that the biofilm on the anodic surface was mature after startup.

Fig. 2 shows the *I*–*V* curves for the tested SMFCs during and after startup. The cathodic/anodic currents were higher for group B and group C cells than for group A and group D cells. Bioelectrochemical activities were identified in the anodic biofilms. However, no oxidization/reduction pairs appeared in these systems. The maximum current densities for group A, group B, group C and group D were 23.6, 59.6, 42.0 and 4.9 mA/m^2, respectively. Hong et al. [23–25] reported a power density of 20–45 mA/m^2 in a freshwater SMFC, which was comparable to that in groups A and C and but lower than that in group B. The low conductivity of fresh water generally yielded a lower electricity yield [26].

The voltages for groups B and C were higher than those for groups A and D, which suggests that the biotic anodes provided much better cell performance compared to abiotic anodes [27]. The voltages for group A (one anode) were higher than those for group D (two anodes); in contrast, the voltages for group B (one anode) were higher than those for group C (two anodes), which indicates that the anodic surface area of SMFC does not correlate with the voltage yielded by the SMFC. This observation does not correlate with those noted in Ref. [28–30]. The inconsistency suggests that the biofilm structure and the associated microbial community have greater impact than electrode surface area to SMFC performance.

Mass transfer effects

Fig. 3 shows the voltage data for the two SMFCs for group A under stirring and no-stirring conditions. The stirring caused a 4-h period of sudden voltage fluctuation followed by a high-voltage (ca. 250 mV) period. The voltage then dropped back to the original value of approximately 160 mV. Repeated stirring yielded similar voltage changes for SMFC. These experimental tests revealed mass transfer resistance at the studied anode surface, which is consistent with the literature [30–34].

The upper water aeration of SMFC increased the cell voltage gradually by 40–60 mV (Fig. 3). This indicated that the mass transfer rate at cathode also contributes to limit the cell performance, which was also reported in Nielsen et al. [35].

Fig. 4 shows the pH and DO distributions for both SMFCs at the end of this stirring-aeration test. The pH was 6.4–6.6 and was uniformly distributed over the sediment height, indicating the occurrence of hydrolysis of organic substances over