Increased Power Generation in a Continuous Flow MFC with Advective Flow through the Porous Anode and Reduced Electrode Spacing

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The maximum power generated in a single-chamber air-cathode microbial fuel cell (MFC) has previously been shown to increase when the spacing between the electrodes is decreased from 4 to 2 cm. However, the maximum power from a MFC with glucose (500 mg/L) decreased from 811 mW/m² ($R_{\text{CE}} = 200 \, \Omega$, Coulombic efficiency of CE = 28%) to 423 mW/m² ($R_{\text{CE}} = 500 \, \Omega$, CE = 18%) when the electrode spacing was decreased from 2 to 1 cm (batch mode operation, power normalized by cathode projected area). This decrease in power was unexpected as the internal resistance decreased from 35 Ω (2-cm spacing) to 16 Ω (1-cm spacing). However, providing advective flow through the porous anode toward the cathode substantially increased power, resulting in the highest maximum power densities yet achieved in an air-cathode system using glucose or domestic wastewater as substrates. For glucose, with a 1-cm electrode spacing and flow through the anode with continuous flow operation of the MFC, the maximum power increased to 1540 mW/m² (51 W/m³) and the CE increased to 60%. Using domestic wastewater (255 ± 10 mg of COD/L), the maximum power density was 464 mW/m² (15.5 W/m³; CE = 27%). Although flow through the anode could lead to plugging, especially for particulate substrates such as domestic wastewater, the system was operated using glucose for over 42 days without clogging. These results show that power output in this air-cathode single-chamber MFC can be increased by reducing the electrode spacing if the reactors are operated in continuous flow mode with advective flow through the anode toward the cathode.

Introduction

Microbial fuel cells (MFCs) use bacteria to directly generate electricity from the oxidation of organic matter (1–5). Electrons produced by the bacteria flow from the anode to the cathode, where these electrons typically combine with protons and oxygen to form water. MFCs can be constructed with the anode and cathode electrodes in two chambers separated by a proton exchange membrane (PEM) or made with both electrodes in a single chamber without a PEM. One of the main applications envisioned for MFCs is wastewater treatment, because it is possible to simultaneously generate electricity while treating the wastewater (6–8). Power densities produced with glucose or acetate are much larger than those obtained with domestic wastewater. These differences in power densities arise from substrate concentration and form (soluble or particulate), intrinsic microbial kinetics, and the complexity of the microbial community in the biofilm that is needed to completely degrade the substrate (9).

Power densities of a MFC can be increased by chemically modifying the anode (10, 11), improving the cathode performance using ferricyanide (12, 13), using strains that produce high concentrations of mediators (14), and removing the PEM in systems having direct-air cathodes (15). Rabaey et al. (14) achieved a power density of 4310 mW/m² using a mediator-producing bacterial enrichment and ferricyanide. However, ferricyanide is not practical for MFC applications for wastewater treatment, as it must be externally regenerated. An advantage of using oxygen at the cathode is that the reaction is self-sustaining. Pt is usually the catalyst for oxygen on cathodes, and although it is expensive, the loading can be reduced to as little as 0.1 mg cm⁻² without affecting power generation (16). Pt can be replaced by less expensive alternatives such as Co-tetramethylphenylporphyrin (CoT-MPP) or iron(II) phthalocyanine (FePc) with equivalent or only slightly reduced performance (16, 17). Incorporation of Mn⁴⁺ or neutral red into the anode has also been show to increase power (10). The long-term performance of these different materials in MFCs is important but it is only just beginning to be studied (16).

Many MFC tests are based on repeated cycles of liquid replacement (fed-batch operation; 12, 14, 15, 18). Practical applications for wastewater treatment will require continuous flow operation, and several new types of systems are being developed for continuous operation. Liu et al. (6) achieved a maximum power density of 26 mW/m² and 80% COD (chemical oxygen demand) removal with hydraulic retention time (HRT) = 6 h using domestic wastewater in a single-chamber system. Min et al. (19) produced 72 mW/m² (9 W/m³) with wastewater and 212 mW/m² (27 W/m³) using glucose in a continuous flow system by placing the electrodes on either side of the PEM. The increase in power found by Min et al. was thought to result from a reduced internal resistance due to the proximity of the two electrodes. Recently He et al. (20) reported a maximum power density of 170 mW/m² (8.7 W/m³) and 90% soluble COD removal using an upflow MFC with flow directed through a high surface area reticulated vitreous carbon anode using artificial wastewater. Rabaey et al. (21) obtained 38 and 27 W/m² (based on total volume in anode chamber) with glucose and domestic wastewater, respectively, with the flow directed through a bed of graphite granules. However, both of these continuous flow systems used ferricyanide solutions and contained a PEM. For air-cathode MFCs operated in fed batch mode, it has been shown that, when the PEM was removed, the maximum power density increased from 262 to 494 mW/m² using glucose and from 28 to 146 mW/m² using domestic wastewater. However, this reactor was not operated in continuous flow mode (15).

It has recently been shown that the maximum power output by an air-cathode MFC could be increased by reducing the distance between the electrodes (22). When the electrode spacing was decreased from 4 to 2 cm in a single-chamber fed-batch system lacking a PEM, the maximum power density...
increased from 720 to 1210 mW/m² (22). This increase in power was shown to be a consequence of the reduced internal resistance with decreased electrode spacing (22). However, there seems to be an optimum spacing of the electrodes for systems using oxygen as the electron acceptor. Placement of the two electrodes directly on opposite sides of a PEM (the smallest possible electrode spacing) in a flat-plate (19) produced 212 mW/m², but another air-cathode system with a 2-cm spacing produced 1210 mW/m², although this system lacked a PEM. We hypothesize that part of this difference in power generation was due to the effects of oxygen diffusion from the cathode into the anode chamber. While removing the PEM has been shown to increase power when the electrodes are distant (15), the PEM also serves to reduce oxygen diffusion into the reactor. MFC systems that have produced the highest reported power densities use ferri-cyanide, and not oxygen, at the cathode (11, 14).

In this paper, we demonstrate that moving the electrodes too close to each other (1-cm spacing) will decrease power output in an air-cathode MFC lacking a PEM, even though internal resistance is reduced. We show that advective flow toward the cathode increases power and Coulombic efficiency to the highest levels so far achieved using MFCs with air-driven cathodes for glucose and domestic wastewater.

Materials and Methods

MFC Construction. MFC designs were adapted from that used in previous fed-batch studies (15). The cathode was prepared by applying a mixture of Pt/C catalysts (10% Pt; E-TEK) using a Nafion solution (5%) (7 µL of Nafion solution/mg of Pt/C catalyst) onto one side of the carbon cloth (30% wet-proofed, E-TEK), producing a final Pt loading of 0.5 mg/cm². The coated cathode was dried for at least 1 day at room temperature before being used. Note that the Nafion is used here as a cathode binder, not as a PEM, as is typically done in hydrogen fuel cells. A PEM was not used in any tests. The anode was made of plain carbon cloth (E-TEK type A, no wet proofing). Cathode and anode surfaces had a projected surface area of 7 cm² (one side). Stainless steel wire was used to connect the electrodes to a resistor (Rex = 1000 Ω, unless stated otherwise).

The spacing of the anode and cathode in a Plexiglas cylinder (3-cm diameter) was varied in order to systematically investigate the effect of electrode spacing on power. For fed-batch tests, the anode was set 2-cm from the cathode with the anode fixed against the Plexiglas wall (Figure 1A). The anode was moved to a distance 1 cm from the cathode with either the anode exposed to both sides of the fluid with the total chamber distance of 2 cm (Figure 1B) or set at 1 cm with the anode against the Plexiglas wall in a chamber only 1 cm long (Figure 1C). In continuous flow experiments the cathode was placed at different distances from the anode by adding 1-cm-long sections in the reactor (Figure 1D,E). The flow was directed through the anode toward the cathode, with the distance between the entrance wall and the anode fixed at 2 cm (Figure 1D). The electrode spacing, X, defined as the distance between the anode and cathode, was set at 1, 2, or 3 cm, resulting in reactor empty bed volumes of 21, 28, and 35 mL and specific surface areas of the cathode electrode per volume of reactor of 33, 25, and 20 m²/m³, respectively. To avoid any loss of activity when changing the electrode spacing, the reactor was placed in an anaerobic glovebox.

MFC Operation. Two separate MFC reactors were used for these studies, with each reactor inoculated once (except as noted below) using domestic wastewater collected from the primary clarifier effluent at the Pennsylvania State University Wastewater Treatment Plant. Each experiment was repeated at least two times, with all data reported as the average of replicate experiments. Before operating the reactor in continuous flow mode, the system was run in batch mode until a stable cycle of power generation was achieved (typically five cycles, with each cycle about 24 h in duration).

The reactor was fed a medium consisting of a phosphate buffer (50 mM), vitamins, nutrients, and minerals (23) and 1 g/L of glucose during start up and 500 mg/L of glucose in other tests. Flow rate was controlled by a peristaltic pump. Tests on electrode spacing were conducted using glucose (500 mg/L) and a fixed flow rate of 3.3 mL/h. The effect of HRT on power generation was examined by maintaining a constant glucose loading rate (1.7 mg/h/glucose) by varying the flow rate and simultaneously varying the glucose concentration between 250 and 1000 mg/L (electrode spacing fixed at 2 cm). To obtain the maximum power density under fixed conditions, the external resistance in the circuit was varied from 50 to 1000 Ω. The feed solutions used in continuous flow tests were continuously sparged with nitrogen gas to maintain anoxic conditions, and all experiments were conducted in a constant temperature room (30 °C).

In some tests, primary clarifier effluent (255 ± 10 mg of COD/L, pH = 7.5) was used as the feed at a fixed flow rate of 6.1 mL/h, with MFCs having an electrode spacing of 1 cm (HRT = 3.4 h) or 2 cm (HRT = 4.6 h). To limit degradation of the organic matter prior to entering the reactor, the wastewater feed bottle for wastewater experiments was placed in an ice bath.

Calculations. Cell voltage was measured across the external circuit containing a resistor using a multimeter and a data acquisition system (Model 2700, Keithly). Open circuit voltages (OCVs) were recorded for at least 24 h, with the open circuit potentials (OCPs) of each electrode measured with respect to the Ag/AgCl reference electrode (EE009 no leak electrode, Cypress Systems). Current density was calculated as I = V/(Rex), where V (mV) is the voltage, Rex (Ω) the external resistance, and A (cm²) the projected surface area of the cathode electrode (unless stated otherwise). Power density was calculated according to P = I(Vex) where the factor of 10 is needed for the given units) and reactor power output was P = Vex/(Rex-n), where V (mL) is the total liquid volume. Coulombic efficiency was calculated as CE = Cp/C0 × 100%, where Cp (C) is the total coulombs calculated by integrating the current over time, and C0 is the theoretical amount of coulombs available based on the COD removed in the MFC. Energy conversion efficiency was calculated as EE = P(Vex) × 100%, where P is the total generated energy calculated by integrating the power over time. E0 is the theoretical amount of energy that can be produced from glucose (2855 kJ/mol) according to the following reaction:

\[ C_{6}H_{12}O_{6} + 6O_{2}(g) \rightarrow 6CO_{2}(g) + 6H_{2}O(l) \]  (1)

Analytics. The chemical oxygen demand (COD) was measured using a standard method (Method 5220, APHA et al. 1995; HACH COD system, HACH Co., Loveland, CO). All samples were filtered through a 0.22 µm (pore diameter) membrane filter prior to COD measurements. COD removal was calculated as ECOD = [(CODin - CODout)/CODin] × 100%, where CODin is the influent COD and CODout the effluent COD.

The internal resistance, Rein, was measured by electrochemical impedance spectroscopy using a PC4/750 potentiostat (Gamry Instruments) with the anode as the working electrode. The cathode was used as counter electrode and reference electrode. Impedance measurements were conducted at open circuit voltage (OCV) over a frequency range of 10² down to 0.1 Hz with a sinusoidal perturbation of 10 mV amplitude.

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Dissolved oxygen (DO) was measured at different locations in the anode chamber using a nonconsumptive probe (FOXY-R probe, Ocean Optics Inc., Dunedin, FL). The probe was calibrated according to manufacturer’s instruction using oxygen-saturated and -depleted samples. In these tests new electrodes were inoculated as described above and run for 15 cycles in batch-fed mode (~24 h per cycle) using 1 g/L glucose with $R_{m} = 1000 \Omega$. DO concentrations were averaged over 10 h, with reported values from four separate experiments. For batch mode measurements, the reactor was filled with deoxygenated medium in an anaerobic glovebox and operated for 4 h prior to initiating DO measurements. DO was sampled at distances of 1, 2, and 3 cm from the cathode.

**Results**

**Effect of Electrode Spacing: Fed-Batch Mode.** When the electrode spacing was reduced from 2 cm (anode exposed to only one side of the fluid; case A in Figure 1) to 1 cm (anode exposed to both sides of the fluid; case B), the maximum power density with glucose (500 mg/L) decreased from 811 to 684 mW/m² (Figure 2). Note that power decreased even though the anode was fully exposed to the fluid on both sides, potentially providing more surface area for bacterial growth. If the anode was placed 1-cm from the cathode and...
exposed to only one side of the fluid (case C), the maximum power density further decreased to 423 mW/m² (Figure 2). Power decreased under these conditions even though \( R_{\text{ext}} \) decreased from 35 (2 cm) to 16 \( \Omega \) (1 cm) (cases A and C). The CE decreased from 28 (A) to 18% (C) with a decrease in the electrode spacing.

The decrease in the power density produced in both cases when the anode was moved closer to the cathode resulted from decreased activity of the bacteria on the anode, as shown by a decrease in the open circuit potentials (OCPs) of the anode. The open circuit voltages (OCVs) measured for these three cases were 0.820 V (A), 0.797 V (B), and 0.783 V (C). The OCPs of the cathode were essentially constant (0.268 V, A; 0.267 V, B; and 0.266 V, C). Thus, the changes in the OCVs were directly a result of the increased anode potentials, which were \(-0.552\, V\) (A), \(-0.531\, V\) (B), and \(-0.516\, V\) (C).

**Effect of Continuous Flow Operation and Flow through the Anode.** When the reactor was operated in continuous flow mode (Figure 1D), with the anode placed against the wall (see Figure 1A) and set 2 cm from the cathode with no flow through the anode, the power was 420 ± 10 mW/m² (Figure 3) (500 mg/L glucose, HRT = 8.4 h, \( R_{\text{ext}} = 1000 \Omega \)). When the anode was placed so that fluid flow was directed through it under continuous flow conditions (Figure 1D, X = 2 cm from the cathode, 500 mg/L of glucose, HRT = 16 h, \( R_{\text{ext}} = 1000 \Omega \)), power output was increased to 490 ± 4 mW/m² (±SD, \( n = 120 \), 40 h of operation). Thus, the combined effects of exposing both sides of the anode to the solution, and providing continuous flow through the anode, increased the power by a factor of 1.17, which is a smaller change relative than that previously obtained by decreasing the electrode spacing from 4 to 2 cm (22). The effect of HRT on these power densities was not a factor for the case of a fixed load at high resistance (i.e. \( R_{\text{ext}}=1000 \Omega \)), as shown below.

**Effect of Electrode Spacing: Continuous-Flow Mode.** When the electrode spacing was decreased under continuous-flow conditions with flow through the anode, power output substantially increased in all cases. At an electrode spacing of 3 cm, the maximum power density, identified by changing the external resistance, was 826 mW/m² (500 mg/L glucose, \( R_{\text{ext}} = 200 \Omega \)). The maximum power increased to 1007 mW/m² (25 W/m², \( R_{\text{ext}} = 200 \Omega \)) when the electrode spacing was 2 cm and further increased to 1540 mW/m² (51 W/m², \( R_{\text{ext}} = 100 \Omega \)) for a 1-cm electrode spacing, resulting in an overall increase in power of 86% relative to the 3-cm spacing condition (Figure 4).

With flow through the anode, the increase in power followed the trend expected from decreased internal resistance in proportion to electrode spacing. There was a 75% overall decrease in internal resistance when the electrode spacing was decreased from 3 to 1 cm, with values of 56 \( \Omega \) (3-cm spacing), 34 \( \Omega \) (2 cm), and 14 \( \Omega \) (1 cm).

We hypothesized that the measured increase in power generation under conditions of advective flow toward the cathode, compared to batch flow, was a result of altered redox conditions within the reactor and therefore examined dissolved oxygen (DO) concentrations in the solution near the anode. Under continuous-flow conditions, DO was not detectable in solution next to the anode surface in the reactor with a 1-cm electrode spacing. However, under batch conditions, measurable dissolved oxygen concentrations were found at distances relevant to the electrode spacings examined here. We measured DO concentrations in the range of 0.05–0.1 mg/L at a distance of 1 cm from the cathode. At a distance of 2 cm, DO concentrations were 0.005–0.01 mg/L, and by 3 cm they were not detectable (<0.005 mg/L).

The Coulombic efficiency and energy recovery were both improved by decreasing the electrode spacing (Table 1). The maximum values obtained for both CE = 60% and EE = 14.6% were obtained when the electrodes were spaced 1-cm apart with advective flow through the anode. Changing the electrode spacing had no substantial effect on the overall COD removal (range of 89–93%). The main reason the COD removal efficiencies are much higher than the CEs is that a large amount of substrate was removed aerobically by bacteria using oxygen that diffused through the cathode, as noted in previous studies (15).

**Power Density and Coulombic Efficiency as a Function of HRT in Continuous-Flow Mode.** The maximum power density increased from 790 mW/m² at HRT = 4.2 h to 1320 mW/m² at HRT = 15.6 h (Figure 5A). We suspect the increase in power was due to a lower velocity, and therefore, a lower shear rate in the fibrous anode as the substrate concentrations in this range used to maintain a constant organic loading rate should not have affected the maximum power generation (15). COD removals at each HRT were 87 ± 5% (4.2 h), 90 ± 3% (8.4 h), and 94 ± 3% (15.6 h). Coulombic efficiencies increased linearly with the current density (Figure 5B).

<table>
<thead>
<tr>
<th>HRT (h)</th>
<th>COD Removal (%)</th>
<th>CE</th>
<th>EE</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.2</td>
<td>87 ± 5%</td>
<td>60%</td>
<td>14.6%</td>
</tr>
<tr>
<td>8.4</td>
<td>90 ± 3%</td>
<td>60%</td>
<td>14.6%</td>
</tr>
<tr>
<td>15.6</td>
<td>94 ± 3%</td>
<td>60%</td>
<td>14.6%</td>
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For example, at HRT = 15.6 h, the CE increased from 9% to 43% as the current density increased from 0.085 mA/cm² to 0.41 mA/cm². For a specific current density, the CE varied inversely with HRT. At a fixed current density of 0.15 mA/cm², for example, the CE was 12% at 15.6 h, 18% at 8.4 h, and 25% at 4.2 h.

**Power Generation from Domestic Wastewater.** The continuous flow system was also tested with domestic
wastewater at a constant flow rate, with two different electrode spacings. The maximum power density for the electrode spacing of 2 cm (HRT = 4.6 h) was 355 mW/m², and the current density was 0.138 mA/cm² (0.337 V, $R_{ex}$ = 350 Ω). The CE increased as the current density increased, as obtained when using the glucose feed, with a maximum CE of 27% at the electrode spacing of 1 cm. However, this CE was lower than that found using glucose. The overall COD removal under these conditions ranged from 40 to 50%.

**Discussion**

Decreasing the electrode spacing reduces the internal resistance of the air-cathode MFC examined here, providing conditions that should lead to increased power. However, power was found to decrease from 811 to 423 mW/m² when the electrode spacing was decreased from 2 cm ($R_{int}$ = 35 Ω) to 1 cm ($R_{int}$ = 16 Ω) with the anode fixed against one side of the reactor. Exposing both sides of the anode to the reactor fluid provided slightly more power (684 mW/m²), but the key to substantially increasing power for this system was to provide advective flow through the anode toward the cathode. With advective flow and the reactor operating in continuous-flow mode, the maximum power increased to 1540 mW/m² (51 W/m³).

The decrease in the power under fed-batch conditions resulted from the increase in the OCP of the anode electrodes. In contrast to the fed-batch results, the anode OCP (and the cell OCV) was essentially constant under continuous flow conditions with flow through the anode. The effect of the OCV on power can be seen from the equation relating the internal and external resistances and the electromotive force (measured as the OCV) (see Supporting Information)

$$ P = \frac{OCV^2 R_{ex}}{A(R_{int} + R_{ex})^2} $$

(2)

where $A$ is the surface area of the electrode (assumed to be the projected surface area). When the electrode spacing was decreased from 2 to 1 cm during fed-batch tests, the OCV decreased from 0.820 to 0.783 V, resulting in a decreased power density, even though the internal resistance was reduced. The decrease in OCV was due to the decrease of the anode OCP (from −0.552 to −0.516 V; vs Ag/AgCl), while the OCP of the cathode was unchanged.

With advective flow through the anode, the OCV did not change (~0.818 V in all tests) and power increased in proportion to the decrease in internal resistance. For example, we calculated using eq 2 and measurements for the 3-cm electrode spacing ($P = 826$ mW/m², $R_{int} = 56$ Ω, $R_{ex} = 200$ Ω) that the maximum power would be $P = 1510$ mW/m² if...
the internal resistance was $R_{\text{int}} = 14 \, \Omega$ with an external resistance of $R_{\text{ex}} = 150 \, \Omega$. This result compares well with the actual observed maximum power density of the 1-cm electrode spacing of 1540 mW/m² for these resistances as a result of the lack of a change in the OCV.

The decrease in the OCP of the anode, and thus the failure of the reactor to increase power with a 1-cm electrode spacing in fed-batch mode operation, was likely a result of oxygen diffusion from the cathode into the anode chamber. When the system is operated in batch mode, 0.05–0.1 mg/L DO was measured at a distance 1 cm from cathode. When the system was operated in continuous flow mode with flow through the anode, there was no detectable DO in the water directly in front of the anode. Thus, it seems likely that the presence of the DO adversely affected the electricity-generating bacteria on the anode, causing a decrease in the OCP of the anode and a reduction in the maximum power output of this system, despite a decrease in the internal resistance. Other tests support the critical role of the redox environment in a MFC. In MFC tests with an obligate anaerobe (Geobacter metallireducens), it was shown that increasing the concentration of suspended cells, or adding an oxygen scavenger such as L-cysteine, increased power output, presumably due to increased oxygen scavenging (24).

Oxygen diffusion through a cathode during start up of an air-cathode MFC, such as the one used here, has also been found to prohibit the acclimation of bacteria to certain substrates (such as ethanol), but acclimation can occur if a PEM is added (25). Oxygen diffusion can be reduced by using a PEM such as Nafion, but this material is still permeable to oxygen (15, 26). Thus, the effect of DO on system performance must be considered to be an important factor in explaining the performance of the batch and continuous-flow systems with reduced electrode spacing.

When the internal resistance of the MFC is high, there may be little observable effects of electrode spacing. For example, Jang et al. (27) found that the maximum power density of 1.3 mW/m² in their system was not appreciably changed when the distance between the electrodes was increased from 10 to 30 cm. Using eq 2 and the values reported in their study ($P = 1.3 \, \text{mW/m² (10 cm)}$ and $1.25 \, \text{mW/m² (30 cm)}$, $OCV \approx 0.52 \, \text{V (10 cm)}$ and $0.48 \, \text{V (30 cm)}$, $R_{\text{ex}} = 100 \, \Omega$ (10 cm) and $200 \, \Omega$ (30 cm), $A = 465 \, \text{cm}^2$), we calculate $R_{\text{int}} = 668 \, \Omega$ for the 10-cm electrode spacing and 690 $\Omega$ for the 30-cm electrode spacing. There was only a small change in internal resistance and therefore little effect of electrode spacing on power under high internal resistance conditions. These results, therefore, further demonstrate the critical nature of obtaining low internal resistance in the MFC in order to increase power generation, as noted by others (14, 20, 24).

Implications for Wastewater Treatment. The MFC tests conducted here primarily were conducted using a pure substrate, although in some tests we used an unfiltered wastewater. It was expected that flow through the anode would lead to plugging due either to biofilm growth or also, in the case of the wastewater, particle capture and clogging. Potential problems with anode fouling were not addressed here, as the focus of this study was to demonstrate the relationship between internal resistance and power production resulting from advective flow and electrode spacing. However, it should be noted that the MFC was operated with glucose for over 42 days and with wastewater for over 100 h, and in both cases, the system did not clog. The failure of the cloth to clog with glucose suggests that biofilm fouling may be much less of a problem with the types of biofilms produced here, which are active at the electrode surface but presumably progressively less active in the biofilm distant from the electrode surface. For particle-laden wastewaters, it may be possible to design anodes materials with larger pore sizes and greater overall porosities to help mitigate the potential for clogging.

The maximum power density achieved here using domestic wastewater (464 mW/m²) is the highest yet obtained for this type of substrate based on anode projected surface area. This is 15.5 W/m², using the total reactor volume, or 47 W/m³, using the volume between the two electrodes (i.e., neglecting the entrance volume prior to flow through the anode). Previous reports of MFCs treating wastewater indicated maximum power densities from 26 to 146 mW/m² (0.2–3.7 W/m³, total reactor volume) using air cathodes (6, 15, 19). Adveective flow through a high surface area graphite granule bed anode was also recently shown to produce 27 W/m² (empty bed volume; equivalent to 48 W/m³ based on anode liquid volume) using ferricyanide as the electron acceptor (21). Thus, forcing the wastewater to through the anode may hold great potential for increasing power output in MFCs when the internal resistance system is low.

The flow of the wastewater through the anode also produced a maximum CE of 27%, which is higher than that previously obtained with domestic wastewater and air-cathodes (7–20%, refs 6, 15, 19). These CEs with wastewater are lower than those values obtained using glucose due to both the type of substrate (glucose versus wastewater) and the fact that the CE increases with power output (see Figure 6). It should be noted that the CEs were evaluated here on the basis of soluble COD removal, consistent with the approach used for other biofilm processes (for example trickling filters; 28, 29), as these systems are effective at soluble, but not particulate, COD removal. Others have found similar reductions in CE using prefiltered wastewater in MFC studies, with a CE = 59% using glucose and a CE = 20% for wastewater (21). The CEs measured here could be different if evaluated on the basis of total COD. Further improvements in power output and current densities will result in increased CEs and greater efficiencies in the conversion of organic matter in wastewater into electricity.

Acknowledgments

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Supporting Information Available

Additional information on MFC calculations and characteristics. This material is available free of charge via the Internet at http://pubs.acs.org.

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