Abstract

Microbial fuel cells (MFCs) can be used to directly generate electricity from the oxidation of dissolved organic matter, but optimization of MFCs will require that we know more about the factors that can increase power output such as the type of proton exchange system which can affect the system internal resistance. Power output in a MFC containing a proton exchange membrane was compared using a pure culture (Geobacter metallireducens) or a mixed culture (wastewater inoculum). Power output with either inoculum was essentially the same, with 40 ± 1 mW/m² for G. metallireducens and 38 ± 1 mW/m² for the wastewater inoculum. We also examined power output in a MFC with a salt bridge instead of a membrane system. Power output by the salt bridge MFC (inoculated with G. metallireducens) was 2.2 mW/m². The low power output was directly attributed to the higher internal resistance of the salt bridge system (199 ± 50 Ω) compared to that of the membrane system (1286 ± 1 Ω) based on measurements using impedance spectroscopy. In both systems, it was observed that oxygen diffusion from the cathode chamber into the anode chamber was a factor in power generation. Nitrogen gas sparging, L-cysteine (a chemical oxygen scavenger), or suspended cells (biological oxygen scavenger) were used to limit the effects of gas diffusion into the anode chamber. Nitrogen gas sparging, for example, increased overall Coulombic efficiency (47% or 55%) compared to that obtained without gas sparging (19%). These results show that increasing power densities in MFCs will require reducing the internal resistance of the system, and that methods are needed to control the dissolved oxygen flux into the anode chamber in order to increase overall Coulombic efficiency.

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1. Introduction

The production of energy from renewable substrates, such as biomass, is important for creating sustainable energy production and reducing global emissions of CO₂. Hydrogen can be an important component of an energy infrastructure that reduces CO₂ emissions if hydrogen is produced from non-fossil fuel sources and used in fuel cells. Hydrogen gas can be biologically produced at high concentration (60%) from the fermentation of high sugar substrates such as glucose and sucrose (Van Ginkel et al., 2001; Logan et al., 2002). However, known fermentation routes can produce only 33% of the maximum potential energy from a sugar...
such as glucose. More commonly, yields of only half this amount are achieved resulting in the remainder of the energy (typically 85%) being tied up in non-fermentable or poorly fermented organic acids and solvents such as acetic acid, butyric and propionic acids, ethanol, and butanol (Grady et al., 1999; Logan et al., 2002).

Instead of producing electricity indirectly from organic materials with biologically-generated hydrogen, it is now known that electricity can be produced directly from the degradation of organic matter in a microbial fuel cell (MFC) (Suzuki et al., 1978; Wingard et al., 1982; Allen and Bennetto, 1993; Kim et al., 2002; Bond and Lovley, 2003; Liu et al., 2004; Liu and Logan, 2004; Oh et al., 2004). A MFC ordinarily consists of two chambers, one anaerobic (anode) and the other aerobic (cathode). In the anaerobic chamber, substrate is oxidized by bacteria and the electrons transferred to the anode either by an exogenous electron carrier, or mediator (such as potassium ferric cyanide, thionine, or neutral red) (Delaney et al., 1984; Siebel et al., 1984; Lithgow et al., 1986; Emde et al., 1989; Emde and Schink, 1990; Park and Zeikus, 2000; Rabaey et al., 2004a,b), or directly from the bacterial respiratory enzyme to the electrode. In the latter case, the MFC is known as a mediator-less MFC (Kim et al., 1999a,b, 2002; Bond and Lovley, 2003; Gil et al., 2003; Chaudhuri and Lovley, 2003; Rabaey et al., 2003; Jang et al., 2004). The anaerobic chamber is connected internally to the aerobic chamber by a proton-conducting material, and externally by a wire that completes the circuit. In the aerobic chamber, electrons that pass along the circuit combine with protons and oxygen to form water. MFCs requiring exogenous mediators have limited practical applications because chemicals used as mediators are expensive and toxic to bacteria (Bond et al., 2002; Bond and Lovley, 2003; Gil et al., 2003; Jang et al., 2004). Mediator-less MFCs have the potential to produce electricity from anaerobic sediments for marine devices (Reimers et al., 2001; Bond and Lovley, 2003) and electricity from sewage (Gil et al., 2003; Liu et al., 2004).

Mediator-less MFCs have only recently been developed, and therefore the factors that affect optimum operation, such as the bacteria used in the system, the type of proton conductive material, and the system configuration, are not well understood. Bacteria in mediator-less MFCs typically have electrochemically-active redox enzymes such as cytochromes on their outer membrane that can transfer electrons to external materials. Several microorganisms that are able to reduce iron have been found to function in mediator-less MFCs, including *Shewanella putrefaciens* (Kim et al., 1999a,b, 2002), several members of Geobacteraceae (Reimers et al., 2001; Bond et al., 2002; Tender et al., 2002; Bond and Lovley, 2003; Jang et al., 2004), fermentative bacteria such as *Clostridium butyricum* (Park et al., 2001), and newly isolated bacteria such as *Rhodoferax ferrireducens* (Chaudhuri and Lovley, 2003). Electricity was generated with these microorganisms and several substrates including glucose (*Rhodoferax ferrireducens*; Chaudhuri and Lovley, 2003), lactate, pyruvate and formate (*S. putrefaciens*; Kim et al., 1999a,b, 2002), benzoate (*G. metallireducens*; Bond et al., 2002; Bond and Lovley, 2003), acetate, and hydrogen (*Geobacter sulfurreducens*; Bond and Lovley, 2003; Pham et al., 2003). Mixed cultures in mediator-less MFCs have also been reported to generate power using specific compounds or organic matter in wastewater and marine sediment (Reimers et al., 2001; Bond et al., 2002; Gil et al., 2003; Rabaey et al., 2003; Liu et al., 2004; Liu and Logan, 2004). Recently, it has been found that a mixed microbial community, consisting primarily of *Alcaligenes faecalis*, *Enterococcus gallinarum*, and *Pseudomonas aeruginosa*, could produce power in a MFC using mediators produced by a bacterial community (Rabaey et al., 2004b).

Proton conductive materials in a MFC should ideally be able to inhibit the transfer of other materials such as the fuel (substrate) or the electron acceptor (oxygen) while conducting protons to the cathode at high efficiency. Materials used in MFCs include fluoropolymer-containing cation exchange materials such as Nafion™ (Park and Zeikus, 2000; Bond and Lovley, 2003; Gil et al., 2003), polystyrene and divinylbenzene with sulfonic acid groups (Kim et al., 2002), dialysis membranes (2000–14,000 Da; Kim et al., 1999a), and even systems without a membrane (Reimers et al., 2001; Bond et al., 2002; Liu and Logan, 2004). Nafion™ is the most intensively studied fuel cell membrane as it provides high ionic conductivity ($10^{-2}\text{S cm}^{-1}$). The main limitations of Nafion™ are its high cost ($780/\text{m}^2$; Reimers et al., 2001), restricted temperature range (less than 100 °C; Basura et al., 1998), and oxygen permeability ($9.3 \times 10^{-12}\text{mol cm}^{-1}\text{s}^{-1}$; Basura et al., 1998). Of these, temperature considerations are not a concern for MFC applications.

In this study, we examined several factors that could affect MFC operation: the type of inoculum (*G. metallireducens* or bacteria present in wastewater); the proton conducting material (a proton exchange membrane or a salt bridge); and methods used to scavenge dissolved oxygen that can leak into the anode chamber through the proton conducting material. We demonstrate for our system that physical factors were more important to maximum power generation than biological factors.

### 2. Materials and methods

#### 2.1. Culture and medium

*G. metallireducens* was grown in anaerobic tubes (28-mL, Belco Glass Inc.) on sodium acetate (1.64 g/L),
ferric citrate (13.7 g/L), and a nutrient medium (NaHCO₃, 3.13 g/L; NH₄Cl, 0.31 g/L; NaH₂PO₄·H₂O, 0.75 g/L; KCl, 0.13 g/L; 12.5 mL each of metal and vitamin solutions) (Lovley and Phillips, 1988). Cultures were maintained by serial transfer (10% inoculum) in bottles containing 20% CO₂ (80% N₂) at 30 °C. Cultures were incubated for 7 days, and then transferred (5% inoculum) into the anode chamber containing fresh medium amended with additional phosphate buffer solution (PBS: Na₂HPO₄, 2.75 g/L; NaH₂PO₄·H₂O, 4.22 g/L) except as noted.

Domestic wastewater was collected from the primary clarifier of the Pennsylvania State University Wastewater Treatment Plant. Primary clarifier effluent was amended with the medium ingredients (except NaHCO₃ and ferric citrate) and PBS (Na₂HPO₄, 2.75 g/L; NaH₂PO₄·H₂O, 4.22 g/L), and used as both as an inoculum and as a medium for growth during the start up of a mixed culture MFC.

The initial pH of all solutions was adjusted to 7, and all MFCs were operated in a temperature-controlled room at 30 °C. In some tests, L-cysteine HCl (0.5 g/L, Calbiochem) was added to chemically scavenge dissolved oxygen. L-cysteine reacts with dissolved oxygen to form cystine, a disulfide-bonded dimer.

2.2. MFC construction and operation

All electrodes were made of carbon paper. The electrodes used in the salt bridge MFC were the same size (1.5 × 4.5 cm) but the cathode was coated with a Pt catalyst on one side (De Nora North America, Inc.). The electrodes used in the membrane MFC were slightly larger (2.5 × 4.5 cm) due to the use of a larger bottle size. Catalyst loaded onto the cathode by the manufacturer was 1 mg/cm² (20% Pt) except as noted (0.35 mg/cm² with 10% Pt) due to lack of availability of the same material at the time of the experiments. Copper wire was attached to the electrodes and all exposed metal surfaces were sealed with a nonconductive epoxy (Dexter Corp., NJ, USA). After drying the electrode was degassed in an airlock chamber and moved into an anaerobic glove box (Coy Scientific Products).

The membrane MFCs (250-mL bottles, Corning Inc., NY, USA; 300 mL capacity) contained a glass bridge to hold the proton exchange membrane (PEM) between the bottles (Fig. 1). The PEM (Nafion™ 117, Du Pont Co., USA) was clamped between the flattened ends of the two glass tubes (total length = 8 cm; inner diameter = 1.3 cm) fitted with rubber gaskets. The anode chamber was filled (250 mL) with medium and PBS and mixed using a magnetic bar. The cathode chamber was filled with PBS and continuously sparged with air.

Salt bridge MFCs were constructed by joining two media bottles (125-mL Wheaton Scientific, NJ, USA; capacity 150 mL) with a U-shaped glass tube salt bridge (length = 30 cm; inner diameter = 0.6 cm) filled with PBS and sealed with one vycor tip on the end of the tube (Princeton Applied Research). The bottles were autoclaved and assembled in an anaerobic glove box (except as noted), filled with medium (130 mL) amended with PBS, and the anode chamber was sealed.

Fig. 1. A membrane MFC consisting of an anaerobic chamber (anode; left) and aerobic chamber (cathode; right) connected by a glass bridge containing a Nafion™ membrane.
with a rubber stopper and cap. The apparatus was removed from the glove box, and the anode chamber was mixed using a magnetic bar. The cathode chamber was filled with PBS and operated as indicated above.

2.3. Analysis

The system was monitored (1 h intervals) using a multimeter (Keithley Instruments, Cleveland, OH, USA) connected to a personal computer. The circuit was completed with a fixed load of 470 or 1000Ω, except when different resistors (22Ω–1 MΩ) were used to determine the power generation as a function of load. Current (i) was calculated at a resistance (R) from the voltage (V) by \( i = V/R \). Power (P) was calculated as \( P = iV \), and normalized by the surface area of the anode. The Coulombic efficiency was calculated by integrating the measured current relative to the theoretical current based on the consumed acetate (Oh et al., 2004). We assumed that acetate (0.5 mM), which was injected into the anode chamber, was completely consumed based on numerous experiments in our laboratory and other reports that shows complete removal of acetate when the voltage decreases to nearly zero (Oh et al., 2004; Bond and Lovley, 2003).

The rate of oxygen diffusion into the anode chamber was determined by monitoring the concentration of dissolved oxygen in the anode chamber using a non-consumptive dissolved oxygen probe (FOXY probe, Ocean Optics, Inc., Dunedin, FL; 0.5 mg/L minimum detection level as reported by the manufacturer). The internal resistance of the MFC was measured using electrochemical impedance spectroscopy (EIS; Solartron Analytical, Hampshire, England). For EIS measurements two chambers were filled with 50 mM phosphate buffer with the pH adjusted to 7. The electrodes were prepared as described above for the different MFC systems.

3. Results

3.1. Membrane MFC using a pure culture

A membrane MFC inoculated with *G. metallireducens* and ferric citrate initially produced very little power (~0.1 mW/m²). Repeated additions of fresh cell suspensions (two times) did not increase the power. The color of the medium in the anode chamber remained a dark brown and did not turn clear, indicating no significant ferric iron reduction. It was suspected that oxygen diffusion from the cathode chamber through the membrane might be limiting microbial activity. Cysteine (0.5 g/L) was added to the anode chamber in order to chemically scavenge any oxygen diffusing into the anode chamber. Cysteine addition at this concentration will completely scavenge dissolved oxygen (initially at saturation) within ca. 10 min (Song and Logan, 2004). Upon cysteine addition, the media color rapidly became clear and the power output increased to 7.8 mW/m². This increase in power generation following the addition of cysteine confirmed that dissolved oxygen was preventing higher levels of power generation. Adding additional cysteine (two times; 0.5 g/L) did not increase power output and abiotic controls using only cysteine and media did not generate any power (data not shown). Thus, it was concluded that the cysteine was not being oxidized by the bacteria and used as a substrate for electricity generation.

Power generation could be increased by adding additional acetate (final concentration of 1.18 g/L; Fig. 2). Over the next 369 h (526–895 h) of operation, power generation averaged 40 ± 1 mW/m². On two occasions (355 and 484 h) the oxygen supply to the cathode was interrupted and power output ceased as the oxygen was consumed in the cathode. Power output was quickly restored following re-aeration of the cathode solution.

Because the bacteria can use ferric iron as an electron acceptor, we wondered if the presence of ferric citrate was limiting power generation. Therefore, following inoculation of a new MFC, ferric citrate was removed from the medium. Power output in the absence of the ferric citrate was only slightly lower (37.2 ± 0.2 mW/m²), indicating that this component had little impact on electricity generation (data not shown). The effect of cysteine on power output was again examined under conditions where ferric citrate was removed from the medium. Following cysteine addition (0.5 g/L), power output was essentially unchanged at 36 ± 1 mW/m² (average over 18 h; data not shown).

3.2. Membrane MFC with a mixed culture

A membrane MFC inoculated with primary clarifier effluent achieved an average power density of 38 ± 1 mW/m² over 71 h (161–232 h) (Fig. 3). This level of power generation was similar to that obtained using *G. metallireducens* in the same reactor setup.

The effect of dissolved oxygen flux into the anode chamber was examined with fresh medium (except NaHCO₃, acetate, and ferric citrate) amended with PBS by sparging the anode chamber with nitrogen gas (7–8 mL/min). Acetate was injected to the anode chamber each time at a final concentration of 29.5 mg/L. The maximum power generated in the presence of gas sparging (33.0 ± 0.3 and 36 ± 1 mW/m²) was similar to that in the absence of sparging (35.4 ± 0.2 mW/m²) (Fig. 4). However, the Coulombic efficiency (CE) was several times larger (CE = 47% or 55%) with nitrogen gas sparging than without sparging (CE = 19%). This
greater Coulombic efficiency was primarily attributed to increased use of the electron donor for electricity generation, although an indirect effect of the shear (through increased mass transfer to the bacteria; Logan and Dettmer, 1990) on the microbial community cannot be discounted.

3.3. Salt bridge MFC with G. metallireducens

The initial voltage produced by a salt bridge MFC during the first 100 h of operation (<5 mV) was substantially increased by changing the resistor from 470 to 1000 Ω (Fig. 5). Over the next 270 h, the voltage
averaged 20 mV (maximum of 22 mV), resulting in an average power density of 0.3 mW/m² with the 1000 Ω resistor. This power generation was an order of magnitude smaller than that achieved with the MFC under the same conditions but using a membrane instead of the salt bridge.

Dissolved oxygen was initially thought to be a factor in the power generated in this system. *G. metallireducens* is an obligate anaerobe and small amounts of dissolved oxygen inhibit cell respiration (Gorby and Lovley, 1991). However, Geobacteraceae are able to scavenge small amounts of dissolved oxygen (Jara et al., 2003) and we wondered if adding bacteria into the liquid suspension to scavenge dissolved oxygen might increase power output. This experiment was therefore repeated using a new anode, but ferric citrate was added into the anode chamber to stimulate the growth of suspended bacteria in the anode chamber. Data collection was begun 24 h after inoculation, and power generation indeed increased from 0.3 to 0.9 mW/m² over the next 93 h suggesting that dissolved oxygen influx into the system was limiting power generation by *G. metallireducens* in this system (Fig. 6). When a chemical oxygen scavenger (cysteine) was injected into the anode chamber at 93 h, power output was unaffected, averaging 0.84 ± 0.02 mW/m² over the next 65 h (93–141 h). The lack of a further increase in power generation with the cysteine suggested that the presence of the suspended bacteria was sufficient to scavenge the oxygen.

3.4. Power and individual voltage measurement as a function of electrical load

In order to determine the maximum power output of the membrane and salt bridge MFCs, the circuit resistance was varied in the range of 12 Ω–1 MΩ (Fig. 7). The maximum power from the MFC with a salt bridge reached 2.2 mW/m² using a 47 kΩ resistor (370 mV), while the membrane MFC generated the maximum power of 38 mW/m² using either a 470 or 1000 Ω resistor (201 and 293 mV, respectively).

3.5. Electrochemical analysis of the MFCs

It was believed that the different power densities produced by the MFCs containing different proton exchange systems resulted from the difference of internal resistance of two systems. Using impedance spectroscopy, it was determined that the internal resistance of the salt bridge MFC was 19920 ± 50 Ω. In contrast, the membrane MFC had a substantially (~15 ×) lower internal resistance of 1286 ± 1 Ω.

Individual electrode potentials were further analyzed using a Ag/AgCl reference electrode to better characterize...
the power generation and the factors affecting power output (Fig. 8). The open circuit potential (OCP) of the membrane MFC was 604 mV, with anode and cathode potentials of \(-438\) and \(163\) mV, respectively. The OCP for the salt bridge MFC was \(560\) mV (\(-409\) mV for anode and \(190\) mV for cathode), which is similar to that
obtained from a membrane MFC system, demonstrating the intrinsic (open circuit) electrode potential was not a factor in the different power densities produced by the two systems. In both cases the cathode potentials (190 mV for the salt bridge and 163 mV for the membrane system) were substantially smaller than the theoretical value of 605 mV, assuming standard conditions and a partial pressure of oxygen of 0.2 atm (Liu and Logan, 2004). Overpotential at both electrodes reduced the working potentials even further. For example, with a 1000 Ω resistor the cathode potential decreased to 22 mV at the highest current density of 130 mA/m² for the membrane system, and to 100 mV (18 mA/m²) for the salt bridge system (Fig. 8).

Fig. 7. Voltage and power generation in (A) salt bridge and (B) membrane MFCs as a function of circuit load (resistance).
3.6. Oxygen diffusion through the proton exchange membrane

The amount of oxygen that diffused through the Nafion membrane was measured based on oxygen accumulation in the anode chamber under abiotic conditions. The rate ($W$) of oxygen diffusion through a membrane of cross section $A$ can be calculated from the flux ($J$) as

$$W = JA = -DA \frac{dC}{dx} \approx -DA \frac{\Delta C}{\Delta x}. \tag{2}$$

For a cross-sectional area of 2.1 cm$^2$, dissolved oxygen at saturation on the cathode side of the membrane ($7.76 \times 10^{-3}$ mg/cm$^3$), a membrane thickness of 190 μm, we obtain a maximum rate of oxygen diffusion into the

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**Fig. 8.** Cell voltage and individual electrode potential in (A) salt bridge and (B) membrane MFCs as function of current density.
anode chamber of 0.014 mg/h and an effective diffusion constant of 2.75 x 10^{-6} cm^2/s. This rate, if maintained at its maximum rate due to utilization on the anode side of the membrane, is equivalent to a loss of 1.4 mg/L of dissolved oxygen per day in the MFC (240 mL). This oxygen flux into the system would require the daily net consumption of 28 mg/L of cysteine.

Similar methods were used to measure oxygen diffusion into the salt bridge MFC. However, we were not able to measure any accumulation of dissolved oxygen in the anode chamber over a 28 h period.

4. Discussion

Power generation using a membrane MFC inoculated with *G. metallireducens* was 37–40 mW/m^2 which was similar (in order of magnitude) to that found by others using *Geobacter* spp. and other pure cultures in two chambered MFCs. Bond et al. (2002) obtained 14 mW/m^2 using a two-chambered fuel cell, while Bond and Lovley (2003) achieved 49 mW/m^2 using *G. sulfurreducens* and acetate-fed membrane (Nafion) fuel cells. These power densities are higher than those reported for MFCs with *Shewanella putrefaciens* IR-1 and lactate (0.6 mW/m^2; Kim et al., 2002) or *Rhodoferax ferrireducens* and glucose (8 mW/m^2; Chaudhuri and Lovley, 2003). The main factor affecting power densities in this system, however, was not the use of a pure culture. Mixed cultures in the same membrane MFC inoculated with wastewater generated a similar power density (38 mW/m^2).

A critical factor in the power density achieved in a two chambered system was the system internal resistance, which was primarily a function of the proton exchange membrane system internal resistance and salt bridge resistance by scaling power output on the basis of power produced in similar conditions (0.3 and 0.84 mW/m^2). This effect of internal resistance can be seen on the basis of power produced in systems relative to their internal (R_i) and external resistances (R_e). Current in a circuit with two resistors in series is calculated as $I = \frac{V}{R_i + R_e}$, and power output is $P = I^2R_e$. Thus, we can compare the membrane and salt bridge by scaling power output on the basis of $P = R_eV^2/R_i^2$, where $R_i$ is the total resistance ($R_t = R_i + R_e$). Using a power density for the membrane MFC of $P_m = 40$ mW/m^2 and internal and external resistances of $R_{i,m} = 1286 \Omega$ and $R_{e,m} = 470 \Omega$, we would predict a maximum power density of the salt bridge MFC ($R_{i,s} = 19,920 \Omega$ and $R_{e,s} = 47,000 \Omega$) of

$$P_s = \frac{P_m \times R_{i,m}^2}{R_{e,m} \times R_{e,s}} \times \frac{R_{e,s}}{R_{i,s}} = 40 \text{ mW/m}^2 \times \frac{(1756 \Omega)^2}{470 \Omega} \times \frac{47,000 \Omega}{(66,920 \Omega)^2} = 2.8 \text{ mW/m}^2.$$ \hspace{1cm} (1)

The calculated power of 2.8 mW/m^2 is similar to the measured maximum value of 2.2 mW/m^2 from the salt bridge MFC. Furthermore, in additional experiments using mixed cultures, we have observed that placing the anode from a membrane MFC into a salt bridge MFC similarly reduces power output. These results, combined with our finding of similar OCPs in the salt bridge and membrane systems, demonstrate how the internal resistance affects power generation in the MFCs.

4.1. Effect of oxygen on power generation in MFCs

Oxygen could diffuse into the anode chamber at a maximum rate of 0.014 mg/h in the membrane MFC, but oxygen diffusion into the salt bridge anode chamber was not detectable. The effect of dissolved oxygen diffusion into the anode chamber will likely vary as a function of the bacteria or microbial community that is present in the system and the ability of these bacteria to respire or scavenge the oxygen. For example, *G. metallireducens* is an obligate anaerobe while *S. putrefaciens* is a facultative anaerobe. The effect of dissolved oxygen on different bacterial strains may partly explain different power densities achieved in different MFCs, but it is likely the physical differences in the MFCs played a larger role. Oxygen diffusion into the anode chamber will affect, however, Coulombic efficiencies. In tests here it was shown that nitrogen gas sparging did not affect power densities but it did increase the Coulombic efficiency of the system.

In order to limit the effect of oxygen on power generation in the MFC, we added cysteine into the anode chamber. The possibility that cysteine also acted as an electron shuttle, or mediator, in this system cannot be ruled out. Doong and Schink (2002) reported that for *G. sulfurreducens* growth on acetate with iron, cysteine functioned as an electron carrier according to first-order kinetics, although they did not examine growth of this microbe in an MFC. If cysteine functioned as mediator, we would expect that increasing the concentration of cysteine would increase power generation. However, when cysteine was added into a reactor already containing suspended cells (that could help scavenge oxygen), power did not increase (Fig. 6). Furthermore, the effect of mediators has been reported to be small for bacteria able to transfer electrons directly to the electrode in an MFC. It was shown using *G. acetoxidans* that addition of the mediator anthraquinone-2,6-disolfonate (AQDS) increased electron transfer by only 24% (Bond et al., 2002). On this percent basis, the contribution of cysteine to power generation would not explain the much larger increase in power (7700%; from 0.1 to 7.8 mW/m^2) observed here when oxygen was thought to be limiting power generation. The presence of an endogenously produced mediator can be detected using cyclic voltammetry (Rabaey et al., 2004b), but it has been reported
that this method failed to demonstrate that cysteine could function as a mediator in a MFC (Logan et al., 2005). Thus, it appears that the main contribution of cysteine in these tests was to function as an oxygen scavenger and not as an electron shuttle. While it remains possible that cysteine contributed to power generation through both oxygen scavenging and the shuttling of electrons, it was not possible to separate these effects in the current study.

4.2. Implications for MFC design and operation

These results show that optimizing power generation in MFCs will require maximizing proton transport rates by reducing the internal resistance of the system and minimizing oxygen transport. Nafion membranes have been extensively used in many MFC studies, and it is clear that oxygen permeability through these membranes can reduce Coulombic efficiency of the MFC. The use of mixed cultures may help minimize the effects of oxygen diffusion into the anode chamber because these bacteria will scavenge any dissolved oxygen, maintaining anaerobic conditions in the anode chamber. Because aerobic bacteria would not contribute to electricity generation, however, any oxygen diffusion into the system will result in a loss of substrate and reduced Coulombic efficiencies. A potential application of MFCs is for power generation from wastewater, including domestic wastewater and a high-starch-content industrial wastewater (Park et al., 2001; Gil et al., 2003; Liu et al., 2004). In cases where these wastewaters are used the loss of substrate may not be an issue as the objective of treatment (organic matter removal) is still accomplished.

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References


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