Scalable air cathode microbial fuel cells using glass fiber separators, plastic mesh supporters, and graphite fiber brush anodes

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\textbf{Abstract}

The combined use of brush anodes and glass fiber (GF1) separators, and plastic mesh supporters were used here for the first time to create a scalable microbial fuel cell architecture. Separators prevented short circuiting of closely-spaced electrodes, and cathode supporters were used to avoid water gaps between the separator and cathode that can reduce power production. The maximum power density with a separator and supporter and a single cathode was 75 ± 1 W/m\textsuperscript{3}. Removing the separator decreased power by 8%. Adding a second cathode increased power to 154 ± 1 W/m\textsuperscript{3}. Current was increased by connecting two MFCs connected in parallel. These results show that brush anodes, combined with a glass fiber separator and a plastic mesh supporter, produce a useful MFC architecture that is inherently scalable due to good insulation between the electrodes and a compact architecture.

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\section{Introduction}

Microbial fuel cells (MFCs) have drawn increasing attention as a promising technology for wastewater treatment and energy recovery (Logan, 2008; Lovley, 2008; Rabaey and Verstraete, 2005). Single-chamber, air-cathode MFCs have the greatest potential for practical applications due to their simple design and the direct use of oxygen in air (Fan et al., 2007; Zhang et al., 2010b). The main challenges for improving MFC performance are increasing power, increasing the recovery of electrons from the substrate (Coulombic efficiency; CE), and reducing material costs in a way that allows for scalable designs.

Power can be increased by reducing the distance between electrodes as this decreases internal resistance (Liu et al., 2005). The use of a separator provides a method to reduce the electrode spacing, insulate the electrodes, and decrease oxygen intrusion into the anode chamber. The use of a cloth separator (J-cloth, JC) substantially improved power generation in an air cathode MFC (Fan et al., 2007), but the cloth was degraded over time (Zhang et al., 2009). Cation (CEMs) and anion exchange membranes (AEMs) are commonly used as separators in MFCs (Kim et al., 2009; Liang et al., 2007; Zhang et al., 2010a), and they are not readily biodegradable. However, they can deform, reducing power densities as a result of water trapped between the membrane and electrode (Zhang et al., 2010a). Membrane deformation can be avoided using a stainless steel mesh supporter to press the membrane against the cathode (Zhang et al., 2010a). Glass fiber mats can be used as separators. They have high proton and low oxygen transfer coefficients, are not biodegradable, and produce low ohmic resistances (Zhang et al., 2009). Scaling up electrodes to larger sizes than those used in the laboratory will require a method to hold the separator in place against the cathode, in order to maintain an open volume for liquid in the anode. Thus, a supporter will be needed for MFCs whether or separators deform.

High volumetric power densities have been achieved using a separator electrode assembly (SEA) architecture (Fan et al., 2007; Liang et al., 2007; Zhang et al., 2009, 2010a) where the separator is sandwiched between two electrodes. In previous MFC tests the anode, separator, and cathode were all flat and pressed together. Carbon cloth is usually used as an anode, but fuel cell grade material can be expensive (approximately $1000/m\textsuperscript{2}) (Logan, 2010). An alternative to a flat anode is a graphite fiber brush (Logan et al., 2007; Nielsens et al., 2007). While a cloth anode can achieve a smaller average distance to the cathode, a graphite fiber brush can have more surface area. Although brush anodes have been used with membrane separators, they have not been previously examined in systems with glass fiber separators.

In this study, the use of plastic mesh as a supporter for a glass fiber separator was examined in brush anode MFCs with different...
configurations (single cathode, two cathodes, and two MFCs wired in parallel). MFCs without a separator or supporting plastic mesh were also studied to determine the effect of these components on performance.

2. Experimental

2.1. MFC reactors

Anodes were ammonia gas treated carbon brushes (Logan et al., 2007). Cathodes were made of carbon cloth (Type B, 30% wet proofing, BASF Fuel Cell, Inc., NJ) with 0.5 mg/cm² platinum (7 cm² projected area) and four polytetrafluoroethylene (PTFE) diffusion layers to prevent water loss and reduce oxygen transfer through the cathode (Cheng et al., 2006a,b). Single-chamber, air–cathode, cubic-shaped MFCs (2-cm long cylindrical chamber; liquid volume 12 mL) were constructed as previously described (Zhang et al., 2009). Polypropylene mesh 1.0 mm thickness (GF1; type DC1.0, Jiafu Co., China) was placed against cathode (MFCs had a second cathode placed on the other side of the chamber (Logan et al., 2007) were placed in the middle of the chamber, with a glass fiber separator, with a material for other separators (such as AEMs).

No. 145872, Spectrum Medical Industries Inc., CA) was used as a supporting material to press the separator against the cathode (except as noted). The different architectures are summarized using the following abbreviations (Fig. 1): GF1–SCa, GF1 separator and plastic mesh (M) supporter with a single cathode (SCa); GF1–SCa, separator and a single cathode but no mesh supporter; NS–SCa, no separator (NS) or mesh supporter; GF1–DCa, GF1 separator, mesh supporter and double cathodes (DCa); GF1M–2DCa, two MFCs each with a GF1M–DCa architecture that are operated in parallel.

Anodes were enriched in MFCs using effluent from an existing MFC (originally inoculated with primary clarifier overflow) operated in fed batch mode for over one year. The MFCs were fed acetate (1 g/L) in a 50 mM phosphate buffer solution containing mineral (12.5 mL/L) and vitamin (5 mL/L) solutions (Logan et al., 2007). MFCs were operated (23 ± 3 °C) until they exhibited stable performance (~7 cycles single cathode, ~14 cycles double cathode). After 20 cycles the plastic mesh support was added to the separator.

2.2. Analysis

Voltage (E) across an external resistor was measured at 20 min intervals using a data acquisition system (2700, Keithley Instrument, OH) connected to a personal computer. Current (I = E/R), power (P = IE) and Coulombic efficiency (CE) were calculated as previously described (Logan et al., 2006), with the current density and power density normalized by the projected surface area of the cathode, and the volumetric power density normalized by the liquid volume. Polarization curves were obtained by varying external resistance with 20 min intervals. Ohmic resistance was determined using electrochemical impedance spectroscopy (EIS) with a potentiostat (PC 4/750, Gamry Instrument Inc., PA) (He et al., 2006; Logan et al., 2007). Impedance measurements were conducted at the open circuit voltage (OCV) over a frequency range of 10,000 to 0.1 Hz with a sinusoidal perturbation of 10 mV amplitude. Ohmic internal resistances of reactors were determined using Nyquist plots (He et al., 2006; Logan et al., 2007).

3. Results and discussion

3.1. Power Generation with a single cathode

Maximum power single-cathode MFCs with the separator and mesh supporter of 75 ± 1 W/m³ (6.0 A/m²) (Fig. 1) was the same as that produced in the absence of the mesh (74 ± 4 W/m³), indicating that the presence of the plastic mesh support did not affect power production (Fig. 1). There was no separator deformation during four months of MFC operation. This result is different from that obtained with ion exchange membranes (AEM and CEM) where power was adversely affected by membrane deformation unless a stainless steel mesh was pressed against the membrane (Zhang et al., 2010a). The lack of an adverse effect on power generation suggests that plastic mesh could be used as the supporting material for other separators (such as AEMs).

Power production was adversely affected by removing the separator. The maximum power decreased to 68 ± 1 W/m³ when the separator and mesh supporter were removed (Fig. 2). The anode potential became more positive in the absence of a separator, likely due to the effect of oxygen intrusion into the anode chamber (Cheng et al., 2006a,b). Removing the separator increased the cathode potential over the current density range of 0.8–5.8 A/m² (Fig. 2), but this was not sufficient to produce a net increase in power production due to the higher potentials of the anode.
The effect of the separator on power generation depended on the electrode spacing and the type of separator. For example, with a CEM in an MFC with a 4 cm (flat) electrode spacing, net power increased when the CEM separator was removed (Liu and Logan, 2004). In MFCs with flat anodes (carbon cloth) and a 2 cm electrode spacing, anode performance was not affected but cathode performance was altered when using other separators (AEM, CEM, glass fiber and J-cloth) (Fig. 2) (Zhang et al., 2010b, 2009). Here, a brush anode was used, so that the spacing of bacteria near the cathode was variable. Some of the bacteria on the brush edge were close to the cathode, but bacteria on other side of the brush were further away from the cathode. The distance of the nearest carbon fibers to the cathode was only ~1–2 mm. When the separator was removed here, both the anode and cathode potentials were affected. This resulted from an adverse effect of oxygen on the anode bacteria when using a brush anode, and a beneficial effect on the cathode likely due to improved proton transfer.

The power densities produced here with a brush anode are higher than those previously obtained with a flat anode (Table S1). This is due to both a larger surface area of the brush anode for exoelectrogenic bacteria growth, and an anode potential that was significantly lower than that of a flat cloth anode (2 cm electrode spacing) under the same solution conditions (Fig. 2). A SEA MFC with a flat carbon cloth anode (12 mL) was previously shown to produce 64 ± 1 W/m³ under otherwise identical conditions (Zhang et al., 2009) (Table S1). Here, in a mixed electrode assembly (MEA) with a brush anode, separator, and a mesh support, the maximum power density (75 ± 1 W/m³) was 17% greater than the SEA (Table S1). Thus, the use of the glass fiber separator and plastic mesh as supporter with a graphite brush anode shows a promising configuration for a multi-electrode MFC design.

3.2. Power generation with double cathodes

Double-cathode MFCs (1000 Ω) required more startup time (14 cycles) than single-cathode MFCs, likely due to oxygen diffusion from the cathode to the anode (Fig. S1). The maximum power density of using a single brush anode in a double cathode MFC was 154 ± 1 W/m³, 108% more than the single-cathode MFC (Fig. 1 and Table S1). The internal resistance of double-cathode MFCs with the separator and plastic mesh was 5.9 ± 0.9 Ω, which was lower than that of single-cathode MFC with the separator and mesh (12.2 ± 0.1 Ω) or the MFC without mesh (11.8 ± 2.1 Ω) (Table S1). This increase in power was a result of the 167% larger cathode surface area per volume (156 m²/m³) of the double-cathode MFCs than single-cathode MFCs (58 m²/m³).

3.3. Double-cathode MFCs operated in parallel

Two double-cathode MFCs (GF1 M-2DC), which had two brush anodes and four cathodes, were operated in parallel to increase current. The maximum power was 2.18 mW, 58% more power than an individual double cathode MFC (1.38 mW), and 142% more than a single-cathode MFC (0.90 mW). The ohmic internal resistance was 4.5 ± 0.4 Ω. The power density of two MFCs in parallel was 121 ± 1 W/m³, slightly lower than that obtained using the individual MFCs (double cathodes) (Fig. 1). Despite this slightly lower power density, this parallel configuration can be useful for scaling up MFCs as the use of multiple cells to increase current can improve the efficiency of DC–DC voltage conversion. MFCs can also be operated in series to increase voltage (Aelterman et al., 2006), but this can result in charge reversal and a loss in power production (Oh and Logan, 2007).

3.4. Coulombic efficiencies

The mesh supporter did not adversely affect CE. Over a current density range of 0.8–4.0 A/m², the CEs ranged from 44% to 77% with and without the supporting mesh (Fig. 1). At a current density of more than 6 A/m², the CEs of the MFCs with mesh were only slightly larger than those without mesh (Fig. 1). The CE at the current density of the maximum power for the MFC with mesh was 83%, compared to 76% for the system without mesh. Removing the separator reduced the CEs (Fig. 1) to a range of 18–55% (0.8–7.2 A/m²). The CE at the current density of maximum power was 50%, which is lower than when a separator was used (45–81% at the same current density range, and CE = 76% at the current density of the maximum power output) likely due to reduced oxygen transfer through the cathode (Zhang et al., 2010b, 2009). CEs for double cathode MFC varied from 44% to 75% at current densities ranging from 1.1 to 5.5 A/m², which was similar to that obtained in single-cathode MFCs at the same current densities (Fig. 1). The CEs for MFCs in parallel was lower than that of the individual MFCs (Fig. 1). The CE at the current density of the maximum power density was 60% (Fig. 1). The individual single-cathode MFC without a separator obtained lowest CE.
3.5. Comparison of GF1, CEM and AEM

When scaling up MFCs, power, CE and cost are all important. Separators can improve performance, but they also can increase material costs. From both a performance and cost perspective, the glass fiber separators are superior to the membrane separators. Maximum power densities with AEM and CEM separators (12 mL volume, brush anode) are lower (46 ± 4 and 32 ± 2 W/m²) (Zhang et al., 2010a) than those with a glass fiber separator (75 ± 1 W/m²). This higher power suggests that the glass fiber material had a higher proton mass transfer coefficient and lower ohmic resistance reactors that used CEMs or AEMs (Zhang et al., 2009). The CE = 83% with a brush anode and a single separator was slightly less than that obtained with an AEM (87%) or CEM (88%) (Zhang et al., 2010a).

The costs for an AEM (AMI 7001S), CEM (CMI 7000S) ($83 per m², $300 per 1.2 × 3 m sheet, 100 + sheet order) and Nafion 117 ($2200 per m², $200 per 0.3 m sheet, 100 + sheet order) are all substantially more than a glass fiber separator ($0.32 per m²). Thus, glass fiber separators and plastic mesh can be used in MFCs to maximize power and CE, and minimize costs.

4. Conclusions

A brush anode, glass fiber separator and plastic mesh supporter produced an MEA that was more effective for power production, and was lower in materials costs, than systems using membranes. Power production was 75 ± 1 W/m² with the MEA, compared to only 46 ± 4 (AEM) or 32 ± 2 W/m² (CEM) with membrane separators (Zhang et al., 2010a). Power was also higher with the brush anode used here, than that previously obtained with a flat carbon cloth anode 64 ± 1 W/m³ (Zhang et al., 2009). These results show the brush MEA configuration is useful for scaling up MFC systems.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.biortech.2010.05.090.

References


