Power generation using an activated carbon and metal mesh cathode in a microbial fuel cell

Fang Zhang a, Shaoan Cheng a,b, Deepak Pant c, Gilbert Van Bogaert c, Bruce E. Logan a,*

a Department of Civil and Environmental Engineering, Penn State University, 212 Sackett Building, University Park, PA 16802, USA
b State Key Laboratory of Clean Energy Utilization, Department of Energy Engineering, Zhejiang University, Hangzhou 310027, PR China
c Separation and Conversion Technology, VITO – Flemish Institute for Technological Research, 2400 Mol, Belgium

Article info

Article history:
Received 28 August 2009
Received in revised form 18 September 2009
Accepted 22 September 2009
Available online 24 September 2009

Keywords:
Microbial fuel cell
Activated carbon
Metal mesh
Cathode

Abstract

An inexpensive activated carbon (AC) air cathode was developed as an alternative to a platinum-catalyzed electrode for oxygen reduction in a microbial fuel cell (MFC). AC was cold-pressed with a polytetrafluoroethylene (PTFE) binder to form the cathode around a Ni mesh current collector. This cathode construction avoided the need for carbon cloth or a metal catalyst, and produced a cathode with high activity for oxygen reduction at typical MFC current densities. Tests with the AC cathode produced a maximum power density of 1220 mW/m² (normalized to cathode projected surface area; 36 W/m³ based on liquid volume) compared to 1060 mW/m² obtained by Pt catalyzed carbon cloth cathode. The Coulombic efficiency ranged from 15% to 55%. These findings show that AC is a cost-effective material for achieving useful rates of oxygen reduction in air cathode MFCs.

© 2009 Elsevier B.V. All rights reserved.

1. Introduction

A microbial fuel cell (MFC) is a novel technology for direct electricity generation from biomass [1–5]. Reducing the cost of the materials used in MFCs is essential for practical applications. The cathode accounts for the greatest percentage of the total capital cost [6], and cathode surface area and materials generally limit higher power production in MFCs [7–9]. Therefore, identifying low-cost materials and efficient cathode architectures are important for improving cost effectiveness and performance of MFCs.

Carbon based materials are widely used as the electrode for air cathode MFCs. The high cost of some of these materials, such as carbon cloth (ca. $1000/m²), prohibits the use of this material for large scale systems. While low cost cathodes have previously been used with precious metal catalysts such as Pt and Pd in hydrogen fuel cells [20]. An AC cloth air cathode was developed that used ethylenediaminetetraacetic acid (EDTA) chelated iron as a catalyst, achieving a power density of 40 W/m³ [19]. However, this system required the use of a cation exchange membrane and a sprinkler system to continuously apply a 0.7% NaCl solution over the cathode. The use of a membrane can increase system cost, and the need for wetting the cathode could complicate operation.

In this study, we examined the use in an MFC of a simple AC air cathode that does not require any additional metal catalysts for efficient oxygen reduction. We built the AC air cathode around a nickel (Ni) mesh current collector in order to allow for ease in scale up to larger cathode sizes. We show that this metal mesh AC cath-
ode is a high performance and cost-effective method for constructing MFCs.

2. Materials and methods

2.1. Electrodes

Cathodes were constructed at VITO (Belgium) by pressing at 150 bar a mixture of AC (70–90 wt%); Norit SX plus, Norit Americas Inc., TX) and polytetrafluoroethylene (PTFE) binder on top of a Ni mesh current collector (#53 mesh, 330 μm opening, 150 μm wire diameter) to form a cathode 0.45 mm thick (final weight ~1 kg/m²). A PTFE diffusion layer (70% porosity, 0.13 kg/m²) was added to the air-side of the cathode, except as noted. In some cases the same cathode additionally contained a Pt/Pd catalyst. These cathodes were compared to a carbon cloth cathode made as previously described (Pt loading of 0.5 mg/cm², Nafion binder) [8,14]. Anodes were ammonia gas treated graphite fiber brushes (25 mm diameter × 25 mm length; fiber type PANEX 33 160K, ZOLTEK) [7].

2.2. MFC construction and operation

MFC tests were conducted using single-chamber, cubic-shaped MFC reactors containing a cylindrical anode chamber 4-cm long and 3-cm in diameter [21]. Reactors were inoculated with solution from an MFC operated for over 1 year (initially inoculated using primary clarifier effluent from a local wastewater treatment plant). The anode was placed horizontally in the cylindrical chamber with the end 1 cm from the cathode. All reactors were operated at 30 °C, and fed a medium containing acetate (1.0 g/L), a phosphate buffer, and trace mineral (12.5 mL/L), and vitamin (5 mL/L) solution [21].

2.3. Calculations

Voltage (E) across the external resistor in the MFC circuit 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 [2], with the current and power normalized by the projected surface area of the cathode or the reactor volume. Power density curves were obtained by varying external circuit resistance, with a single resistor used for a full batch cycle.

Linear sweep voltammetry (LSV) was used at a scan rate of 1.0 mV/s to evaluate the electrochemical performance of the cathodes as previously described [12]. Energy dispersive X-ray spectroscopy (EDS) was performed to analyze the elemental composition at a sampling depth of up to 1–2 μm. Plain AC cathodes and AC cathodes with Pt/Pd were analyzed by EDS at 20 kV (Quanta 200, FEI, OR).

3. Results and discussion

3.1. MFC performance

Plain AC cathodes produced a maximum power density of 1220 ± 46 mW/m² with a PTFE diffusion layer, and 1150 ± 57 mW/m² without a diffusion layer (Fig. 1A). In addition to a lower power density, the AC cathode lacking the PTFE layer also exhibited more erratic performance, as shown by high standard deviations for values obtained in duplicate tests (Fig. 1A). For comparison with cathodes previously used in this reactor, a maximum power density of 1060 mW/m² was produced using a carbon cloth cathode with Pt (0.5 mg/cm²). Power production was increased by only 16% (1415 mW/m²) by adding a Pt/Pd catalyst, compared to much larger increases observed for carbon cloth with Pt [14].

The open circuit cathode potential of the AC cathode with a PTFE diffusion layer was 430 mV, and decreased from 222 mV at a current density of 0.7 A/m² (1000 Ω) to ~34 mV at a current density of 6.9 A/m² (50 Ω). CE increased from 15% to 55% with increasing current density (Fig. 1B).

During initial MFC tests, we observed appreciable water losses based on the development of a headspace in the anode chamber. We therefore pierced the septum on the top of the reactor with a needle connected to a 5 mL syringe containing deionized water, and measured daily water losses of 10–15% of the liquid in the reactor. The inclusion of a PTFE diffusion layer did not substantially affect water losses, suggesting that water losses were due to evaporation and not flow thorough the cathode. Water losses could be reduced in the future by using more dense diffusion layers.

3.2. Electrochemical performance

LSV tests were conducted to evaluate the electrochemical performance of the AC cathodes. Plain AC cathodes were compared to carbon cloth and AC cathodes containing Pt/Pd. At a current density of less than 3.9 A/m², the AC cathode exhibited better electrochemical performance than Pt loaded carbon cloth cathode (Fig. 2). Addition of Pt/Pd to the AC cathode improved performance, with the higher current densities produced at all voltages compared to the other two cathodes.

3.3. Elemental composition

EDS analysis showed that for plain AC from cathode, carbon and fluorine were two most abundant elements, with trace amounts of...
calcium, iron, aluminium, and nickel (Table 1). The presence of fluorine was due to the use of the PTFE binder, and the Ni on the AC was likely due to the process of pressing the AC onto the Ni mesh. The acid washed AC used here should have had a low metal content. Analysis of the AC containing Pt/Pd showed that it contained at the surface 4.42% Pt and 2.52% Pd (Table 1). These two precious metal catalysts were responsible for the improved performance of the AC electrode.

3.4. Performance and cost of materials

The performance of the AC cathodes was due to the high surface area of the material, combined with the effective current collection by the Ni mesh. The PTFE diffusion layer contributed to consistent performance, although it did not sufficiently limit water losses through the cathode. Such water losses may not be important in continuous flow systems, but in fed-batch systems this results in the development of a headspace.

The cost of the AC cathodes cannot be predicted with any certainty, but we estimate a reasonable market price to be $50–70/m² when produced in reasonable sized batches. The price of just the AC is only ca. $2.60/kg, which is sufficient to produce a 7 m² electrode. Building the cathode around the metal mesh lowers the ohmic losses of cathode, and avoids the need for other support materials such as membranes. The cost of the cathode can be further reduced to $20–40/m² through using less expensive materials and minimizing the amount of metal used for the current-collecting mesh. Preliminary tests with much less expensive stainless steel mesh have shown MFC performance comparable to that of the Ni mesh (unpublished results). The fact that stainless steel can replace the Ni suggests that the Ni is not acting as an oxygen reduction catalyst. PTFE was used here as a binder and diffusion layer, but it may be possible to use less expensive materials in the future.

4. Conclusions

Inexpensive AC was used at cathode without any metal catalyst for oxygen reduction in an air cathode MFC. The use of this AC cathode in an MFC produced a maximum power density of 1220 mW/m² (36 W/m³) compared to 1060 mW/m² obtained by Pt catalyzed carbon cloth cathode, and CE ranging from 15% to 55%. Thus, the use of AC and a metal mesh collector is an efficient and cost-effective method for producing an air cathode for an MFC. Further improvements in the performance of AC cathodes should be possible to limit water losses and further reduce the costs of these cathodes.

Acknowledgements

The authors thank D.W. Jones for help with the analytical measurements and M. Hazen for EDS analysis. This research was supported by Award KUS-I1-003-13 from the King Abdullah University of Science and Technology (KAUST). The research at VITO is supported by a Grant from Milieu en Energietechnologie InnovatiePlatform (Project M8463 – Sewage Plus).

References


Fig. 2. LSV of plain AC, AC with Pt/Pd and Pt catalyzed carbon cloth cathode.