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Increasing power generation for scaling up single-chamber air cathode microbial fuel cells

Shaoan Cheng [a,b], Bruce E. Logan [b,*]

[a] State Key Laboratory of Clean Energy Utilization, Department of Energy Engineering, Zhejiang University, Hangzhou 310027, PR China
[b] Department of Civil and Environmental Engineering, 212 Sackett Building, Penn State University, University Park, PA 16802, USA

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ABSTRACT

Scaling up microbial fuel cells (MFCs) requires a better understanding the importance of the different factors such as electrode surface area and reactor geometry relative to solution conditions such as conductivity and substrate concentration. It is shown here that the substrate concentration has significant effect on anode but not cathode performance, while the solution conductivity has a significant effect on the cathode but not the anode. The cathode surface area is always important for increasing power. Doubling the cathode size can increase power by 62% with domestic wastewater, but doubling the anode size increases power by 12%. Volumetric power density was shown to be a linear function of cathode specific surface area (ratio of cathode surface area to reactor volume), but the impact of cathode size on power generation depended on the substrate strength (COD) and conductivity. These results demonstrate the cathode specific surface area is the most critical factor for scaling-up MFCs to obtain high power densities.

1. Introduction

Microbial fuel cells (MFCs) are devices that use microorganisms to catalyze the conversion of chemical energy in organic compounds into electrical power. They have great potential as a technology for sustainable bioenergy production due to their ability to generate electricity from wastewater while simultaneously treating wastewater (Logan and Regan, 2006). Several types of MFCs have been developed, including two-chamber (Oh and Logan, 2006), single-chamber (Liu et al., 2005a), upflow (He et al., 2006), flat (Min and Logan, 2004), and tubular (Zuo et al., 2007) designs. Most of these systems have been studied in the laboratory using high substrate concentrations and well buffered solutions (Liu et al., 2005a; Park and Zeikus, 2002). Electricity generation has also been demonstrated with different types of wastewaters, including domestic, food processing, and animal wastewaters (Liu et al., 2004; Rozendal et al., 2008). Among the different types of MFCs that have been developed, the air cathode MFC is the most likely configuration to be scaled up for wastewater treatment due to its high power output, simple structure, and relatively low cost. Solution conditions such as pH (Raghavulu et al., 2009), temperature, ionic strength (Liu et al., 2005b), and substrate concentration (Liu et al., 2004) can also affect power generation.

Through optimization of MFC architecture and solution chemistry the maximum power densities of MFCs with oxygen have reached 6.9 W/m^2 (power normalized to the anode area) (Fan et al., 2008), or 1.55 kW/m^3 (power normalized to the reactor volume) (Fan et al., 2007). With a ferricyanide as catholyte, a maximum power density of 2.15 kW/m^3 was produced using a small liquid volume (0.336 mL anode volume) (Nevin et al., 2008). These achievements indicate the MFC technology could advance to conventional anaerobic digesters in the term of power density, under optimized conditions (Rabaey and Verstraete, 2005).

High power densities have only been achieved using laboratory-scale MFCs and liquid volumes less than 30 mL (Zhang et al., 2010a,b,c). When MFCs sizes have been tested at the scale of several liters or more, reported volumetric power densities generally have been lower, and typically less 35 W/m^3 (Dekker et al., 2009; Liu et al., 2008). This suggests that scaling factors have not been well understood or controlled. In most cases the main reason for low power densities is a high internal resistance which can be due to anode and cathode overpotentials, substrate concentration, membrane resistance, and solution resistance (Clauwaert et al., 2008). To minimize internal resistance, electrodes should be designed to reduce electrode overpotential. High surface area materials and different surface treatments have been used to increase anode performance (Cheng and Logan, 2007; Logan et al., 2007). Increasing the anode surface area can significantly increase power density in smaller (28 mL) reactors (Logan et al., 2007), but it did not appear to increase power in a larger (520 mL) MFC of a similar

* Corresponding author. Tel.: +1 814 863 7908.
E-mail address: blogan@psu.edu (B.E. Logan).

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design (Liu et al., 2008). Changing the solution composition can improve power densities in both larger and smaller systems, especially when solution conductivity is initially low. Increasing the ionic strength of larger MFC from 100 to 300 mM, for example, increased power by 25% (Liu et al., 2008). In a 20 L stacked, two-chamber MFC, cathode performance was improved by decreasing the pH, sparging with pure oxygen instead of air, and increasing the flow rate, resulting in a volumetric resistivity decrease to 1.2 $m\Omega/m^3$ and a power density increase to 144 W/m^3 (Dekker et al., 2009). Balancing pH by using completing the liquid loop over cathode and anode (Clauwaert et al., 2009), or adding CO_2 to cathode to minimize pH imbalance in both anode and cathode chamber of two-chamber MFCs (Fornero et al., 2010) also increased power generation, but the additional energy demands for recycling the flow and the need for a membrane are detrimental aspects of these approaches.

It is generally thought that the cathode surface area limits power production, but this is based on laboratory studies with highly optimized solution conditions of feed strength (acetate concentration) and solution conductivity (buffer concentration). In addition, most previous studies have focused on a single type of reactor with acetate and buffer solutions, and not wastewater. Thus, little has been done to examine the importance of electrode surface areas, cathode performance and reactor geometry relative to solution conditions such as conductivity and substrate concentration relative to both idealized and actual wastewaters. Such information is needed in order to scale up MFCs and achieve high power densities with wastewater treatment systems. In this paper, we systematically varied substrate concentration using acetate, and conductivity, and then examined the effects on power using different cathode specific surface areas. We examined trends in cathode sizes using the acetate and wastewater solutions based on the data obtained here, combined with results from others. We show that cathode surface area is always important for increasing power, but that the cathode size has a much less appreciable impact on power generation with an actual wastewater due to limiting factors of wastewater strength (COD) and solution conductivity.

2. Methods

2.1. Microbial fuel cells

Single-chamber air cathode microbial fuel cells (MFCs) with four different liquid volumes having varied cathode specific surfaces areas were used in this study (Fig. 1). All reactors used the same type of anode brushes consisting of graphite fibers and a titanium core as previously described (Logan et al., 2007), but the brush size varied with the scale of the reactor. All cathodes contained a Pt catalyst and four diffusion layers prepared as previously described (Cheng et al., 2006a) in order to optimize cathode performance in these comparisons.

A 28-mL MFC was constructed as previously described (Logan et al., 2007) and used to study the effect of substrate concentration and solution conductivity on the electrode performance and power density. The specific surface area of the cathode for this MFC was 25 m^2/m^3.

A 250-mL MFC was constructed from a rectangular plastic container by cutting a 4 cm × 6 cm hole on each of the four sides, and placing air cathodes over each hole (sealed with Aquarium Sealant). A single graphite brush anode (5 cm in diameter, 7 cm in length) was suspended in the middle of the container. This 250-mL MFC was used to investigate the effect of cathode surface area on power generation. Cathode surface area was increased from 24 to 48, 72 and 96 cm^2 by connecting the additional cathodes in series, resulting in the cathode specific surface areas of 9.6, 19, 29 and 38 m^2/m^3.

Two larger but differently shaped MFCs were used to study the effect of reactor shape and cathode surface area on power generation, in order to see which design resulted in higher power densities. A 1-L MFC was made from a cylindrical container by cutting two holes on the side of bottle covering them with an air cathode. The cathode active area was 132 cm^2, producing a cathode specific surface area of 13 m^2/m^3. A single graphite brush anode (5 cm in diameter, 14 cm in length) was suspended in the middle of the bottle.

A larger 1.6-L MFC was constructed in the same plate-shaped arrangement as the 28 mL reactor, using four brush anodes [each 5 cm in diameter, 7 cm in length (Logan et al., 2007)] and one or two cathodes (one on each side). The cathode surface area with both cathodes was 290 cm^2, resulting in the cathode specific surface area of 9.1 m^2/m^3 with one cathode, or 18 m^2/m^3 (using two cathodes).

2.2. Inoculation and operation of MFCs

All MFCs were inoculated with a suspension of bacteria from an existing MFC fed operated for approximately two years, and enriched with an external resistor of 1000 Ω. After inoculation with a 50:50 mixture of inoculum and medium, the MFCs were fed only the 100 mM phosphate buffer solution containing 1 g/L (except as noted) sodium acetate and nutrient medium containing 0.31 g/L NH_4Cl, 0.13 g/L KCl, 12.5 mL/L mineral solution, and 5 mL/L vitamin solution (Liu et al., 2005a). The feed solution was replaced when the voltage dropped below 20 mV, forming one complete cycle of operation.

The maximum power densities were calculated from polarization curves obtained either using linear sweep voltammetry (LSV) or by varying the external resistance (1000–50 Ω). LSV curves were obtained using a potentiostat (PC4/750 potentiostat, Gamry Instrument Inc., PA) from the open circuit voltage (OCV)

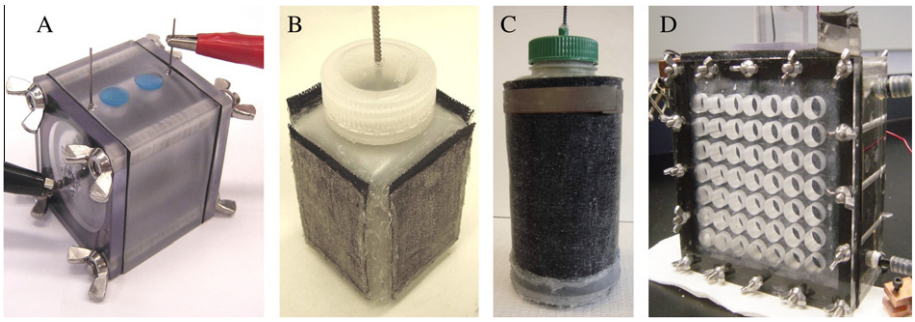

Fig. 1. Single chamber air cathode microbial fuel cells with different sizes, 28 mL (A); 250 mL (B); 1 L (C); 1.6 L (D).