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Electricity generation of single-chamber microbial fuel cells at low temperatures

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ABSTRACT

Practical applications of microbial fuel cells (MFCs) for wastewater treatment will require operation of these systems over a wide range of wastewater temperatures. MFCs at room or higher temperatures (20–35 °C) are relatively well studied compared those at lower temperatures. MFC performance was examined here over a temperature range of 4–30 °C in terms of startup time needed for reproducible power cycles, and performance. MFCs initially operated at 15 °C or higher all attained a reproducible cycles of power generation, but the startup time to reach stable operation increased from 50 h at 30 °C to 210 h at 15 °C. At temperatures below 15 °C, MFCs did not produce appreciable power even after one month of operation. If an MFC was first started up at temperature of 30 °C, however, reproducible cycles of power generation could then be achieved at even the two lowest temperatures of 4 °C and 10 °C. Power production increased linearly with temperature at a rate of $33 \pm 4\,mW\,°C^{-1}$, from $425 \pm 2\,mW\,m^{-2}$ at 4 °C to $1260 \pm 10\,mW\,m^{-2}$ at 30 °C. Coulombic efficiency decreased by 45% over this same temperature range, or from CE = 31% at 4 °C to CE = 17% at 30 °C. These results demonstrate that MFCs can effectively be operated over a wide range of temperatures, but our findings have important implications for the startup of larger scale reactors where low wastewater temperatures could delay or prevent adequate startup of the system.

1. Introduction

Microbial fuel cells (MFCs) directly convert chemical energy in organic matter into electrical energy using microorganisms, providing a method for simultaneously producing renewable energy while treating wastewater (Ahn and Logan, 2009; Feng et al., 2008; Liu et al., 2004; Min and Logan, 2004). Power densities produced with pure compounds such as acetate have increased by nearly six orders of magnitude through improvements in reactor architecture (Logan and Regan, 2006a,b), optimization of solution chemistry (Feng et al., 2008; Liu et al., 2005), and using new materials and modifying electrode surfaces (Cheng and Logan, 2007; Logan et al., 2007; Park and Zeikus, 2003; Zhang et al., 2009). Characteristics of the substrates and system operation also can greatly affect power densities. These include solution pH (Borole et al., 2008; Fan et al., 2008); wastewater alkalinity, added buffers and their concentration, ionic strength, and solution conductivity (Huang and Logan, 2008a; Liu et al., 2005); operation mode in terms of fed-batch or continuous flow (Ahn and Logan, 2009; Huang and Logan, 2008b); and the specific organic matter species in the different types of wastewater and their degradation by products (Feng et al., 2008; Huang and Logan, 2008a; Liu et al., 2004; Min et al., 2005).

Temperature is another important wastewater characteristic, but most studies have examined performance at a single temperature, with typical temperatures chosen of room temperature or higher (20–35 °C). When temperatures have been varied during a study, different results have been obtained relative to impact of temperature on performance, although in almost all cases lowering the temperature reduced performance. In two different studies with single-chamber MFCs operated in fed-batch mode, the power density decreased by 10% when the temperature was reduced from 32 °C to 20 °C (Liu et al., 2005; Wang et al., 2008). In another study with a single-chamber MFC operated with continuous mode, the power density decreased by 21% when the temperature decreased from 35 °C to 24 °C, but only by 5% when the temperature was decreased from 30 °C to 24 °C (Moon et al., 2006). In contrast, it was reported that when using a two-chamber MFC with a ferricyanide cathode, that the power density was reduced by 39% when for a temperature decrease from 30 °C to 22 °C, and that there was no appreciable power generation at 15 °C (Min et al., 2008). In another two-chamber MFC study with a dissolved oxygen (DO) catholyte, however, current increased from 0.7 mA to 1.4 mA when the temperature decreased from the range of 20–35 °C to 8–22 °C (Jadhav and Ghangrekar, 2009). In this case, the solubility of DO may have

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been a factor. The DO saturation concentration varies with temperature, and DO concentrations will affect cathode performance (Oh et al., 2004). The maximum voltages produced in the study by Jadhav and Ghangrekar (2009) were usually very low (<50 mV), and thus other factors such as high internal resistance, changes in microbial community, and DO could have been important. Sediment MFCs have been operated at low and ambient temperatures of seawater, but power densities in these systems are very low, and the effects of temperature on these systems have not been investigated (Reimers et al., 2006). *Geobacteraceae* isolated at 10 °C have been shown to grow at temperatures as low as 4 °C (Holmes et al., 2004b).

The specific temperature may affect what bacteria are present in the anodic biofilms in wastewater fed systems. Changes in microbial communities in response to different treatment conditions and types of organic matter are being studied (Logan, 2009; Logan and Regan, 2006a; Xing et al., 2009). As yet there have been few direct connections between the types of microorganisms that predominate in these systems and power, except that various *Geobacter* species are often associated with higher power densities (Holmes et al., 2004a; Ishii et al., 2008). Thus, while bacterial growth rate and respiration can change with temperature (Madigan and Martinko, 2006), the community development and structure can also be important. In recent field tests, it was found that a 1000-L microbial electrolysis cell (MEC) reactor (Logan, 2010) had a long startup period when inoculated with wastewater and operated at relatively lower temperatures, compared to reactors typically operated in the laboratory at 20 °C or 30 °C (unpublished results). Therefore, it became important to better understand the effects of temperature on MFC startup and operational performance.

In this study, we examined MFC performance as a function of the initial temperature over a range of 4–30 °C. We compared system performance under these different initial temperatures with performance of systems started up at the same time under more optimal temperature of 30 °C which were then switched to operation at lower temperatures.

2. Materials and methods

2.1. MFC construction

MFCs were single-chamber, cube-shaped reactors having a cylindrical anode chamber 4 cm long and 3 cm in diameter as previously described (Liu and Logan, 2004). The anode was an ammonia gas treated graphite fiber brush (25 mm diameter × 25 mm length; fiber type PANEX 33 160K, ZOLTEK) (Logan et al., 2007). Carbon cloth cathodes (7 cm^2) contained a Pt catalyst (0.5 mg cm^{-2}) on the water facing side, and four polytetrafluoroethylene (PTFE) diffusion layers on the air-facing side (Cheng et al., 2006).

2.2. Inoculation and operation

Reactors were inoculated with the solution from an MFC operated for over 1 year (initially inoculated from the effluent of the primary clarifier of the local wastewater treatment plant). After startup, the MFCs were operated in fed-batch mode using a phosphate buffer nutrient solution (PBS; conductivity of 7.8 mS/cm) containing 1 g/L acetate as the fuel (Cheng and Logan, 2007). Temperatures were set at 4 °C, 10 °C, 15 °C, 20 °C, and 30 °C during inoculation and operation using either a constant temperature room or an incubator (SHAKA4000-7, Thermo Scientific). In the case of the lower-temperature tests (4 °C and 10 °C), separate MFCs were also first inoculated and operated at 30 °C for 500 h before being tested at the lower temperature. Reactors were refilled each time

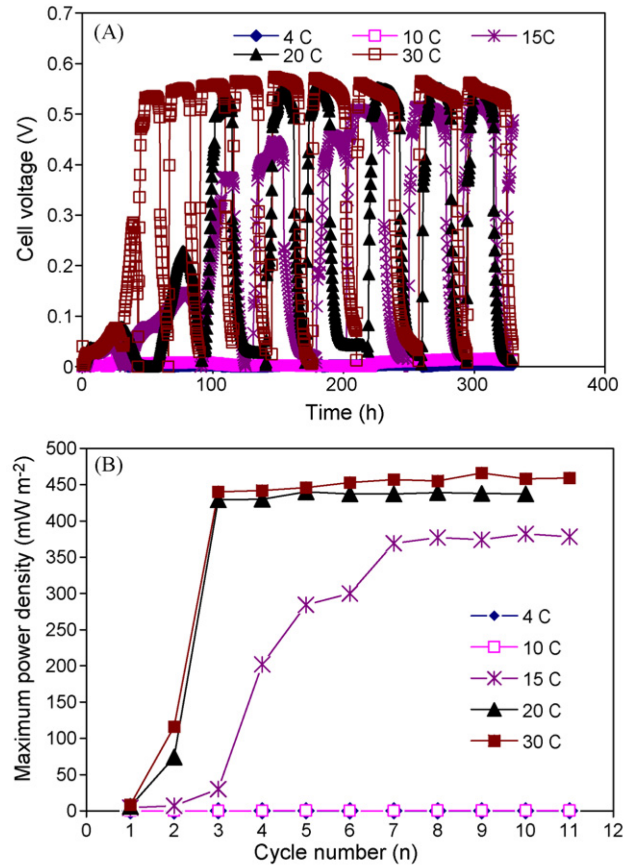

Fig. 1. Voltage generation of MFCs as (A) a function of time and (B) the maximum power density produced in each cycle during the startup period at different temperatures.

when the voltage decreased to <20 mV, forming one complete cycle of operation.

The polarization and power density curves were obtained by operating MFCs for 20 min at different fixed external circuit resistances (1000–50 Ω). Electrode potentials were measured using an Ag/AgCl reference electrode (RE-5B; BASi, West Lafayette, IN), with all potentials corrected and reported here versus a normal hydrogen electrode (NHE). CODs were measured using standard methods (APHA, 1998).

2.3. Calculations and measurements

Voltage (E) across the external resistor (1 kΩ, except as noted) was measured at 20 min intervals using a data acquisition system (2700, Keithley Instrument, OH) connected to a personal computer. Current, power 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.

3. Results

3.1. Startup under different initial temperatures

At 30 °C, MFCs required only ∼50 h (three cycles) before reaching maximum power production (Fig. 1). Cell voltages over subsequent cycles were then reproducible in terms of maximum voltage, with an average of 563 ± 6 mV. When the MFC was initially operated at 20 °C, the time required to reach the first maximum power cycle was still three cycles, but the time required