Biosensors and Bioelectronics 79 (2016) 327–333

Contents lists available at ScienceDirect

Biosensors and Bioelectronics

journal homepage: www.elsevier.com/locate/bios

Characterization of a microfluidic microbial fuel cell as a power generator based on a nickel electrode

Mohammad Mahdi Mardanpour, Soheila Yaghmaei *

Department of Chemical and Petroleum Engineering, Sharif University of Technology, Azadi Avenue, P.O. Box 11365-9465, Tehran, Iran

ARTICLE INFO

Article history:
Received 2 October 2015
Received in revised form
10 December 2015
Accepted 12 December 2015
Available online 15 December 2015

Keywords:
Microfluidic microbial fuel cell
Nickel electrode
Escherichia coli
Glucose

ABSTRACT

This study reports the fabrication of a microfluidic microbial fuel cell (MFC) using nickel as a novel alternative for conventional electrodes and a non-phatogenic strain of *Escherichia coli* as the biocatalyst. The feasibility of a microfluidic MFC as an efficient power generator for production of bioelectricity from glucose and urea as organic substrates in human blood and urine for implantable medical devices (IMDs) was investigated. A maximum open circuit potential of 459 mV was achieved for the batch-fed microfluidic MFC. During continuous mode operation, a maximum power density of 104 W m^{-3} was obtained with nutrient broth. For the glucose-fed microfluidic MFC, the maximum power density of 5.2 μW cm^{-2} obtained in this study is significantly greater than the power densities reported previously for microsized MFCs and glucose fuel cells. The maximum power density of 14 W m^{-3} obtained using urea indicates the successful performance of a microfluidic MFC using human excreta. It features high power density, self-regeneration, waste management and a low production cost (< $1), which suggest it as a promising alternative to conventional power supplies for IMDs. The performance of the microfluidic MFC as a power supply was characterized based on polarization behavior and cell potential in different substrates, operational modes, and concentrations.

1. Introduction

The microbial fuel cell (MFC) is an energy-harvesting platform incorporated into renewable energy stored in organic substances, particularly in wastewater, to produce bioelectricity and simultaneous wastewater treatment (Papaharalabos et al., 2015; Zhou et al., 2014). The intrinsic advantages associated with microfluidic devices result from scale-dependent processes of transport phenomena providing enhanced biofilm growth on anode electrodes with shorter startup times (Choi, 2015). The novel application of microfluidic MFCs in implantable medical devices (IMDs) as power generators, biosensors, and for microbial screening has increased in interest (Mink et al., 2014; Mukherjee et al., 2013; Dong et al., 2013; Oncescu and Erickson, 2011).

Suitable operation of active IMDs, such as muscle stimulators, neuroprosthetic devices, and biosensors, relies on a continuous supply of electricity (Han et al., 2010; Oncescu and Erickson, 2011). Problems associated with conventional IMDs relate to the use of lithium batteries (low lifespan and difficult replacement) and nuclear batteries (potential radioactive risk and expense). The provision of energy to IMDs in a safe, efficient, and continuous manner is extremely important to biomedical engineering and related research fields (Oncescu and Erickson, 2011; Han et al., 2010).

Microfluidic MFCs are self-regeneration and efficient power supplies that compare favorably to conventional batteries and enzymatic systems (Kedzierski et al., 2012). The current bottleneck in development of microfluidic MFCs as IMDs relates to the feasibility of using non-pathogenic bacteria to oxidize human excreta (such as excess blood glucose and urine) to produce long lifetime bioelectricity.

For a microfluidic MFC structure the effect of electrodes on the rate of substrate degradation and electron transfer from the bacteria to the anode that eventually determines the output power and treatment efficiency is crucial (Qian and Morse, 2011). The low power generation and high internal resistance of microfluidic MFCs have attracted academic efforts related to electrode preparation and fabrication (Wang and Su, 2013; Papaharalabos et al., 2015; Choi, 2015).

The applicability of nickel electrodes in an medical implantable devices such as implantable nickel hydrogen batteries (Purushothaman and Wainright, 2012), nickel–cadmium batteries (MacLean et al., 1994), glucose biosensors (Zhu et al., 2012), and hemoglobin biosensors (Tian et al., 2013) has been reported. Robust nickel as a stable, low-cost electrode with high mechanical strength (Huang et al., 2015) has been developed as a surface for

* Corresponding author.
E-mail address: yaghmaei@sharif.edu (S. Yaghmaei).

http://dx.doi.org/10.1016/j.bios.2015.12.022
0956-5663/

biofilm growth and its performance compared with conventional electrodes.

The present study evaluated nickel as a novel alternative for conventional electrodes in microfluidic MFCs to improve power density and reduce the cost of materials for medical usage. The feasibility of a microfluidic MFC as an efficient power generator for production of bioelectricity from glucose and urea as organic substrates in human blood and urine for IMDs was investigated for the first time. *Escherichia coli*, which normally live in the lower intestine and are an important part of a healthy human intestinal tract, were used as biocatalysts in the microfluidic MFC. The capability of extracellular electron transfer of a non-phatogenic strain of *E. coli* increased the possibility of it use as a biocatalyst in microfluidic MFCs to generate power in IMDs.

2. Materials and methods

2.1. Bioelectrochemical microfluidic reactor assembly

Fig. 1 is a schematic of a microfluidic MFC. It was constructed using Poly methyl methacrylate (PMMA) plates as the main body; a single microchannel (1 mm in depth; 1 mm in width; 8 cm in length) was cut using a laser beam as an anodic compartment. A nickel plate (0.5 mm in thickness; 1 mm in width; 5 cm in length) was glued to one side of the anodic compartment. The carbon cloth cathode (5 cm in length and 3 mm in width) was fabricated as described by Cheng et al. (2006) to result in 0.5 mg cm^{-2} of platinum loading. The cathode was placed in front of the nickel anode. The setup operated under ambient conditions. The use of comparatively inexpensive materials and the ease of application strengthen the feasibility of the microfluidic MFC configuration as an implantable power supply and biosensor for medical usage.

2.2. Microfluidic MFC microbial culture

Escherichia coli ATCC-11105 were obtained from the Biochemical and Bioenvironmental Engineering Center of Sharif University of Technology and cultured in the nutrient broth (NB) medium (1 g l^{-1} beef extract, 2 g l^{-1} yeast extract, 5 g l^{-1} peptone, and 5 g l^{-1} NaCl) under anaerobic conditions at 37 °C. The process was performed in both batch and continuous modes under open circuit conditions. During inoculation, whenever the open circuit potential dropped to below 5 mV, the microorganism was fed fresh medium. To allow continuous running of the microfluidic MFC, feed was injected at different substrate rates (50 µl h^{-1}–5 ml h^{-1}) using a syringe pump (New Era; NE-4000; USA). A stable cell potential peak indicated that the biocatalyst had stabilized and microbial enrichment was successful.

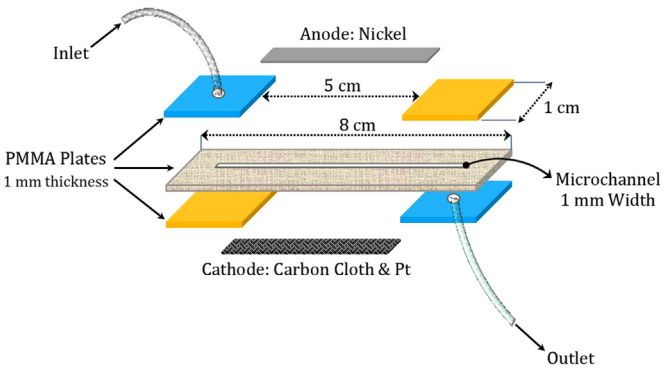

Fig. 1. Schematic details of microfluidic MFC.

2.3. Electrochemical analysis of microfluidic MFC

Cell potential (V) was recorded automatically at 1 min intervals using a data logger connected to a personal computer. Microfluidic MFC characteristics of current (I) and power (P) were calculated versus variable external resistance (1–100 kΩ) and these parameters were then normalized using anodic compartment volume as described by Logan et al. (2006b). Variable external resistance was used to polarize the microfluidic MFC and monitor current variation under closed-circuit conditions to produce polarization and power density curves.

3. Results and discussion

3.1. Open circuit potential

At high external resistance, formation of biofilm with uniform morphology which facilitates electron generation and transfer has been demonstrated (Zhang et al., 2011; Mardanpour et al., 2012; Naraghi et al., 2015). Microfluidic MFC operation was thus initiated under open circuit potential (OCP) conditions for uniform and effective biofilm formation.

When the OCP dropped in batch mode, the full volume of the anodic compartment of the microfluidic MFC (50 µl) was replaced with fresh medium. Fig. 2a shows the 11 feed refreshments carried out during batch operation (denoted by arrows). As long as microbial inoculation continued during OCP evolution, the dynamic response of the system to refreshment of the consumed substrate was evident (Mardanpour et al., 2012; Naraghi et al., 2015). In comparison with previously reported microfluidic MFCs with relative long start-up times (Qian et al., 2011), the expeditious production of bioelectricity from the modified microfluidic MFC in the present study should be noted. This can be attributed to the hydrophilic nickel potential which rapidly absorbs the anolyte and immediately promotes the attachment of biocatalyst to the nickel (Huang et al., 2015).

After a temporary increase in cell potential to 228 mV, the cell potential dropped continuously until the first feed refreshment of the substrate was carried out. Because there was no significant increase in cell potential after 73 min of microfluidic MFC operation, a second refreshment of the substrate was implemented. By continuing fresh feed injections, a maximum OCP of 459 mV was obtained for the microfluidic MFC. The increase observed in the stationary phase of OCP evolution (denoted by dashed arrow in Fig. 2a), indicates the increase in biofilm thickness and bacterial growth associated with substrate refreshment (Mardanpour et al., 2012). Consecutive stable cell potential peaks indicate that the biocatalyst had stabilized and microbial enrichment was successful.

During continuous operation of the microfluidic MFC, five flow rates were examined for the substrate (denoted by differently shaped arrows as five discrete zones in Fig. 2b). The anolyte flow rate was administered at 50 µl h^{-1} (as shown in zone 1). The initial OCP of the microfluidic MFC was 311 mV; after 176 min, the OCP abruptly dropped to 96 mV then rebounded to its initial value over 285 min of microfluidic MFC continuous operation. This descending phase was also observed in the flow rate after the second substrate injection (zone 2 of OCP evolution) and was likely a consequence of complex factors in the medium, such as metabolic disturbance of the microfluidic MFC biocatalyst and distinct oxidation rates of the organic substrates (Naraghi et al., 2015).

In the succeeding steps, microfluidic MFC operation proceeded by increasing the flow rate of fresh feed to 1 ml h^{-1}. As long as microbial enrichment continued during OCP evolution, the