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Enhanced power generation in a single-chamber dynamic membrane microbial fuel cell using a nonstructural air-breathing activated carbon fiber felt cathode

Xinyang Li[a,b], Guicheng Liu[c,d,*], Fujun Ma[a,b], Shaobin Sun[a,b], Siyu Zhou[a,b], Ryanda Enggar Anugrah Ardhi[c], Joong Kee Lee[c], Hong Yao[a,b,1]

[a] School of Civil Engineering, Beijing Jiaotong University, 3 Shangyuancun, Beijing 100044, PR China
[b] Beijing Key Laboratory of Aqueous Typical Pollutants Control and Water Quality Safeguard, Beijing 100044, PR China
[c] Center for Energy Storage Research, Green City Research Institute, Korea Institute of Science and Technology (KIST), Hwarang-ro 14-gil 5, Seongbuk-gu, Seoul 02792, Republic of Korea
[d] Department of Physics, Dongguk University, Seoul 100715, Republic of Korea

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ABSTRACT

A single-chamber dynamic membrane microbial fuel cell (SC-DM-MFC) that uses an activated carbon fiber felt (ACFF) non-structural air-breathing cathode was designed for enhanced power production. The effect of COD loading rate (based on glucose substrate) on power production by SC-DM-MFC was studied. In order to investigate the impact of natural breeze on the performance of SC-DM-MFC via increased air flow, the effect of cathode fanning was studied. The maximum power density increased with an increase in the loading rate from 0.6 to 2.0 gCOD L^{-1} d^{-1} and fanning the cathode improved the power density from 2023 mW m^{-3} to 4653 mW m^{-3}. This increase is attributed to the unique nonstructural design of the cathode that allows both sides of ACFF to reduce oxygen in ambient air. Furthermore, the performance of SC-DM-MFC and a dual-chamber dynamic membrane microbial fuel cell (DC-DM-MFC) was compared. In the comparison test, seafood-processing wastewater was used as a substrate because of its high conductivity, biodegradable properties, and rich nutrient content that make it suitable for the growth of electrogenic bacteria. The results show that it is feasible to generate power in DM-MFCs using seafood wastewater and that SC-DM-MFC performs significantly better than DC-DM-MFC. Enhanced power production can be achieved by using an air-breathing ACFF cathode with nonstructural properties.

1. Introduction

To solve the energy crisis and environment pollution problems, new clean energy technologies need to be urgently developed [1]. Fuel cells are electrochemical devices that convert chemical energy into electricity [2]. And they have been considered a promising clean energy conversion technology [3]. Microbial fuel cells (MFCs) are emerging bio-electrochemical devices that convert chemical energy into electricity using bacteria as catalysts [4]. By generating power from a substrate that is endlessly renewable and simultaneously treats wastewater, MFCs have shown great potential to help alleviate the future energy crisis [5].

An MFC consists of an anode, a cathode, and sometimes a membrane or a separator between the electrodes. Electrogenic bacteria cultivated on the surface of the anode oxidize reduced substrate material to produce protons and electrons, and use the attached anode as the electron acceptor [6]. Protons are transferred in the electrolyte fluid through the separator, and the electrons are conveyed through the external circuit. Then, protons react with electrons and oxygen at the cathode surface to produce water. Although research on microbial fuel cells has shown significant improvement in recent years, there are still many limitations in their practical applications. Some of the constraints are the separators and cathodes of microbial fuel cells [7]. Various types of materials have been used as separators, including anion exchange membranes [8], cation exchange membranes [9], ultrafiltration membranes [10], and other coarse-pore filter materials [11], e.g., J-

* Corresponding author at: Center for Energy Storage Research, Green City Research Institute, Korea Institute of Science and Technology (KIST), Hwarang-ro 14-gil 5, Seongbuk-gu, Seoul 02792, Republic of Korea.
E-mail addresses: log67@163.com, D15604@kist.re.kr (G. Liu), hyao@bjtu.edu.cn (H. Yao).
[1] Co-corresponding author.

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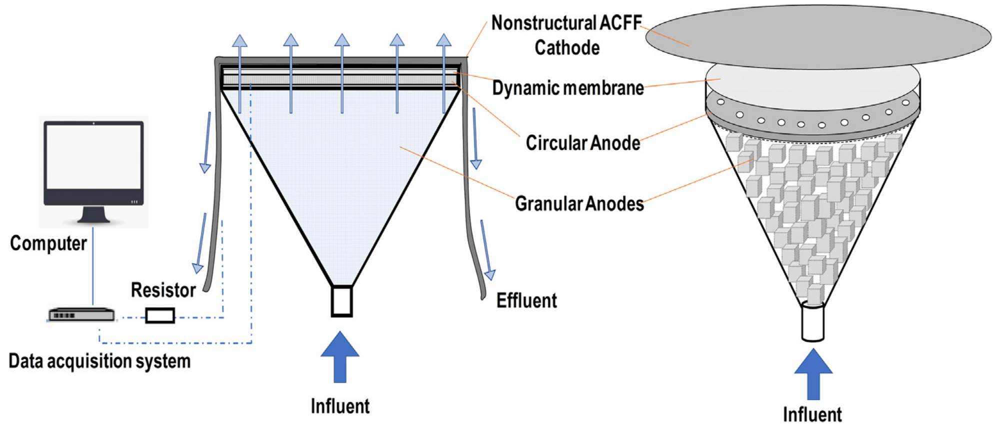

Fig. 1. Schematic construction of single-chamber dynamic membrane microbial fuel cell (SC-DM-MFC).

cloth [12] and glass fibers [13]. Although some progress in the separators has been made in the past decade, the ion exchange membranes still have relatively high ohmic resistance [14], while non-ion selective separators such as glass fibers and J-cloth are prone to transfer oxygen from the cathode chamber to the anode chamber. In our previous study [15], novel dynamic membranes that consist of a supporting layer and a microorganism layer were used as separators in the MFCs. A dual-chamber dynamic membrane MFC (DC-DM-MFC) was developed. Owing to the dynamic membrane's low ohmic resistance, low oxygen diffusion coefficient ($D_0 = 1.8 \times 10^{-7}\,cm^2\,s^{-1}$), and low cost (0.3 USD m^{-2}), the DC-DM-MFC, which has the advantages of traditional dynamic membrane reactors and MFCs, shows a great potential for practical applications including wastewater treatment. However, these dual-chamber MFCs have inherent drawbacks such as the requirement for an aeration system to continuously provide an electron acceptor, i.e., oxygen to cathodes, resulting in the consumption of external power.

Instead of supplying oxygen to the cathode by mechanical aeration in a separate cathode chamber, using an air-cathode that uses oxygen directly from ambient air has recently become a popular method [16]. Air-cathode systems reduce energy demand by eliminating the need to aerate the cathode chamber [17]. This method allows for a single-chamber MFC with a simpler construction. However, previous air-cathodes were located on the side of the reactor and thus served as a structural barrier between the substrate and the outside environment [18]. If the cathode were punctured, the structural integrity of the MFC would be compromised and the substrate would leak from the reactor, resulting in the disruption of the operation. Generally, cathode material and surface area play an important role in MFC power production [19]. Recently, Deng et al. found that ACFF is an ideal carbonaceous material for the cathode [6]; owing to its high specific surface area ($1000\,m^2\,g^{-1}$) and excellent cathodic oxygen reduction ability, ACFF yielded higher power densities than other carbon-based cathodes, e.g., carbon paper, platinum-coated carbon paper or granular carbons [20]. ACFF is also inexpensive, widely available [21], and has a great potential for MFC applications.

In this study, a single-chamber dynamic membrane MFC (SC-DM-MFC) was designed. In this system, an ACFF was used as the air-breathing cathode. Since the cathode does not act as a structure of the traditional single-chamber MFCs, the large-scale operation and maintenance could be simplified. The start-up of SC-DM-MFC and the effect of the chemical oxygen demand (COD) loading rate and the cathode fanning on power production were investigated using glucose as substrate. The feasibility of power production using seafood-processing wastewater as substrate was also studied. Finally, the performance SC-DM-MFC and DC-DM-MFC was compared.

2. Experimental

2.1. SC-DM-MFC set-up

The MFC reactor was constructed in a plastic funnel with an upper diameter of 12 cm. Twenty-one holes with 1 mm diameter each were evenly drilled on a circular carbon felt anode (12 cm diameter, 1 cm thick, $60.5\,m^2\,g^{-1}$ specific surface area, Sanye Co. Beijing, China) to allow the electrolyte to pass through. Another granular anode (16.7 g of carbon felt granules, 3.0 cm × 2.0 cm × 0.5 cm), obtained by cutting a large piece of carbon felt, was placed inside the funnel body. The round anode was installed in the wide top part of the funnel, while the granular anodes filled the funnel and were placed underneath the round anode. A non-conducting nylon net separator (0.03 cm pore diameter, 0.0225 cm thick, Huawei Co., Beijing, China) was placed atop the anode to prevent contact with the cathode.

A circular ACFF cathode (Senxin, Liaoning, China; 50 cm diameter, 0.5 cm thick, $1000\,m^2/g$ specific surface area) was fitted to the top of the funnel with excess fabric draping over the side of the reactor for optimal oxygen absorption (Fig. 1). A carbon thread was tied around the top of the funnel on the outside of the cathode and attached to the anode through a hole in the lower part of the funnel, providing an external circuit. The total empty volume of plastic funnel reactor was 430 mL. After the funnel was stuffed with granular anodes and a circular anode, the actual volume of the reactor was changed to 150 mL. The influent (simulated glucose wastewater) was pumped from the narrow inlet to the wide end of the funnel using a peristaltic pump (BT300-2J, rated input power of 48 W, Lange Co., Hebei Province, China); thus, fluid flowed upward through granular anodes, the round anode, and then through a circular ACFF cathode, successively. To test the effect of COD loading rate on power generation, COD concentrations of 300, 500, and 1000 mg/L in the influent were used. To test the effect of fanning on power production, an electric fan (FSJ4072B, rated input power of 56 W, wind velocity of 3.5 m/s, Haier Co., Qingdao, China) was installed below the cathode to blow the cathode up and provide more oxygen. In order to compare the performance of the proposed SC-DM-MFC with our previously studied dual-chamber dynamic membrane MFC (DC-DM-MFC) with empty volume of 1.1 L (under optimal conditions) [15], a type of wastewater with high salinity, high content of biodegradable organics and nutrients, called seafood-processing wastewater was used as substrate for both DM-MFCs.

2.2. Inoculation and operation

The anodes of SC-DM-MFC and DC-DM-MFC were inoculated using a granular anaerobic wastewater sludge from the Gaobeidian Domestic Wastewater Treatment Plant in Beijing, China. After being washed three times with distilled water, 100 mL of the sludge was added to