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Exposing effect of comb-type cathode electrode on the performance of sediment microbial fuel cells

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HIGHLIGHTS

- The cathode with exposed area can increase the power performance of SMFCs.
- 3.21 times of current density reach at an optimal exposed area of cathode.
- Internal resistance obviously reduces with an optimal exposed area of cathode.
- This design of SMFCs is easy to operate.

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ABSTRACT

Sediment microbial fuel cells (SMFCs) are an innovative, green technology with great potential, and they utilize a voltage drop of redox potential between aerobes and anaerobes to produce electricity and degrade organic wastewater. However, the power performance and degradation rate in SMFCs are limited by the low concentration of dissolved oxygen on the cathode. Therefore, in this study, SMFCs with comb-type cathode electrodes with carbon cloths exposed partly to air and embedded partly in the reactor substrate were designed and operated. They were utilized for enhancing the power density and the effect of three different exposed areas of cathode electrode for improving transfer of oxygen. Results showed that the power density reached 3.77×10^{-2} mW/m^2 for 75% of the (M_{A75}) exposed area, which was 1.93 times than that of 50% of the (M_{A50}) exposed area and 6.44 times than that of 0% (i.e., completely immersed; M_{A0}) exposed area. These results indicated that the exposed area of the cathode electrode had a positive effect on the power performance of SMFCs and would reduce the impedance of the cathode. These findings would apparently offer useful information on the feasibility of SMFCs for wastewater treatment applications in the future.

1. Introduction

Microbial fuel cells (MFCs), a technology with an extremely high potential for practical applications are bio-electrochemical devices that can degrade organic matter in wastewater to produce electricity by redox reactions [1–3]. Although MFC technology has made great advancements in recent years, several achievements are still to be made [1]. One of the most important challenges is the high internal resistance in MFCs which results in potential drop and power reduction [4,5]. The main source of internal resistance is the proton exchange membrane (PEM) which separates the anode chamber and cathode chamber [5]. Thus, as a measure to overcome this issue, single-chambered MFC (SCMFC), which are devoid of a PEM are proposed [6].

This research study focused on sediment microbial fuel cells (SMFCs) which are a type of single-chamber MFCs. Sediments, which contain about 0.4–2.2% organic carbon, can provide exoeletrogens with sufficient substrate to process respiration [7] and then generate electrons to the anode placed inside the sediments [8]. It is worth mentioning that the SMFCs have a biocathode by which the reduction reaction is catalyzed by microorganisms [9,10]. Compared with an abiotic cathode, the biocathode might improve the sustainability of MFCs [11] and avoid nitrate compounds [12–14]. In addition, they do

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not employ expensive catalysts, mediators and PEM and this makes them cost-effective and more competitive [15]. Due to the characteristics mentioned above, SMFCs have lots of potential for future applications. For instance, it can be designed into the sensors in remote areas for power supply. Huang et al. [16] set up an underwater energy harvesting system which supplied sustainable electricity to drive the remote sensing and surveillance devices. Thomas et al. [17] also successfully used a single SMFC to power the wireless sensor network without any external control on the system. Furthermore, it can be combined with wastewater treatment plants for better wastewater treatment. In general, energy efficiency optimization will be considered when designing and constructing wastewater treatment plants and it is an essential element for constructing energy self-sufficient wastewater treatment plants [18]. Some studies have found that when the MFC system was integrated into the wastewater treatment plants, the sludge production and the energy consumption can be reduced significantly, compared with that without MFCs [19,20]. Recently, Trapero et al. [21] assessed the economic value of MFCs integrated into a juice processing plant, and the results showed that MFC systems indeed had potential to replace the aerated activated sludge which was an energy-intensive process of wastewater treatment. However, in order to successfully transform SMFCs into a practically possible technology and reliable energy source, more research must be carried out.

In terms of enhancing the performance of SMFCs, several methods have been proposed and reported. Anode materials with high conductivity, stability and good redox reversibility, such as carbon and graphite can be used [22]. The surface contact angle and wettability can be changed by surface modification which leads to better adhesion of microorganisms [23]. To shorten the startup time and raise the power performance, 3-D micro-emulsion doped anodes which can release lactate slowly were used [24]. Many researches have been performed by adding different substrates like glucose, chitin [25] and acetate [26] to the sediments, as organics can enhance the performance of SMFCs. Moreover, to raise the coulombic efficiency, conductive materials like graphite flakes could be added to the sediment bed [27]. A cathode with good electron transfer efficiency and oxygen reduction rate is quite crucial [28]. In fact, some researchers have pointed out that cathodes would be the limiting factor for power performance and one of reasons for that is the occurrence of tri-phase (solid catalyst, oxygen, and electron) reaction on the surface of electrodes [1]. Among those three materials in the tri-phase reaction mentioned above, oxygen, which is the acceptor of electrons, plays a vital role in the SMFC. However, the solubility of oxygen in water is only 4.6×10^{-6} (25 °C) and much less than that in the air (0.21) [1]. To increase the dissolved oxygen (DO), different kinds of methods have been proposed (Table 1). It is worth to mention that although lots of methods and designs were put forward, like air cathode [29] and plant rhizosphere cathode [30], the studies which really focused on improving the concentration of DO on cathode of SMFCs are less. So, in depth research has to be carried out on optimization of the cathode design in SMFCs which possess large potential for application. He et al. [31] have showed that the power density increased from 29 to 49 mW/m^2 by a rotating cathode which can supply additional oxygen. Wang et al. [23] utilized the floating biocathode (FBC) to avoid the negative influence of DO depletion and had a better power performance than the platinum catalyzed carbon paper cathode. Moreover, the column which contained a biocathode with half of it suspended above water surface had higher DO concentrations than that with a totally submerged biocathode [32]. In other words, it implied that the exposed area of the biocathode might have a positive effect towards the performance of SMFCs. Thus, the different areas exposed to the air have been tested for the suitable ratio based on the area of the anode. The results of this experiment could provide useful information in the design of biocathodes in SMFCs.

Table 1
Different methods used to increase dissolved oxygen (DO) in water.

Methods to increase DO	References
Rotating cathode	[31,33]
Floating cathode	[23,32]
algae cathode	[34,35]
Plant rhizosphere cathode	[30,36,37]
Air cathode	[29,38,39]

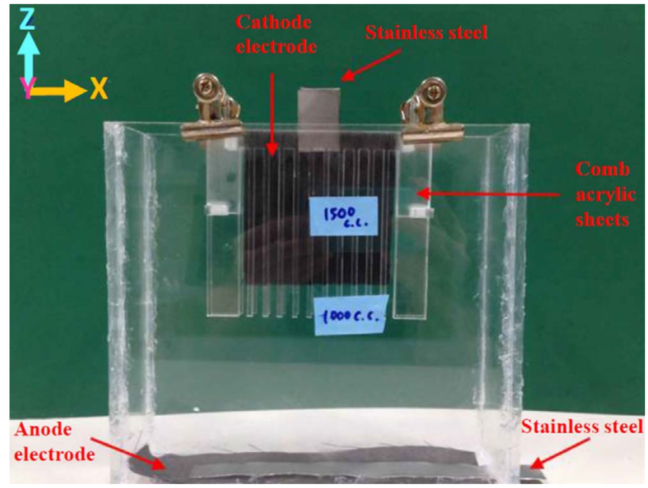

Fig. 1. The structure of a sediment microbial fuel cell (SMFC).

2. Materials and methods

2.1. Construction of sediment microbial fuel cell system (SMFC)

The SMFC used for this research study was designed using acrylic sheets, and the structure of the SMFC is shown in Fig. 1. The size of the chamber was 1.85×10^{-3} m^3 (0.2 m × 0.05 m × 0.185 m). The inoculated solution of the SMFC was wastewater from the Department of Biotechnology and Animal Science, National Ilan University, Yilan, Taiwan, with a working volume of 1.5×10^{-3} m^3. The anode and cathode electrodes were made of pretreated carbon cloth [40]. The working area of the anode was 0.01 m^2 (0.2 m × 0.05 m). Two carbon cloths were used as cathode electrodes with working area of 0.0128 m^2 (0.08 m × 0.08 m × 2) respectively. In addition, two comb acrylic sheets were used to fix the cathode and were placed on the top of the chamber. Two sheets of stainless steel were also fixed to the cathode to accept electrons from the anode. In this study, three ratios of exposed area were used: (1) exposed area equal to 0.0192 m^2 (ratio of exposed area by 75%, M_{A75}) (2) exposed area equal to 0.0128 m^2 (ratio of exposed area by 50%, M_{A50}) (3) exposed area equal to 0 (ratio of exposed area by 0%, M_{A0}). Gupta et al [41] reported that sodium acetate as substrate had a better ability of transferring electrons. Therefore, 1 g of sodium acetate was added into this system at the beginning of the experimental study. Some studies [1,42,43] pointed out that the cathode would be a limiting factor in power performance. Thus, the soaked area (Fig. 2) of the cathode was considered as the working area.

2.2. Experiment method and data collection

The polarization curve was measured by electrochemical analyzer (Jiehan 5600, Taiwan). In addition, the scan rate was set as 0.001 V/s for potentiodynamic analysis. The function P = IV was utilized to calculate power density (PD = P/A). In this study, the soaked area would be regarded as working area A. The electrochemical impedance spectroscopy (EIS) analysis was done at OCV conditions by using AC impedance spectroscopy (HIOKY 35522-50 LCR HiTESTER, Japan) for