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Performance of liter-scale microbial fuel cells with electrode arrays: Effect of array pattern

Xun Zhu [a,b,*], Liang Zhang [a,b], Jun Li [a,b], Qiang Liao [a,b], Ding-ding Ye [a,b]

[a] Key Laboratory of Low-grade Energy Utilization Technologies and Systems, Chongqing University, Ministry of Education, Chongqing 40003, China

[b] Institute of Engineering Thermophysics, Chongqing University, Chongqing 400030, China

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ABSTRACT

Scale-up of microbial fuel cells requires the application of compact structure with well-arranged multi-electrode. For better understanding of electrode design, two liter-scale microbial fuel cells with staggered array (MFC-S) and inline array (MFC-I) were constructed using graphite rod electrodes. The effects of electrode array pattern on MFC startup, power generation, anodic current distribution, COD removal and coulombic efficiency were evaluated. The results showed that MFC-S had a faster startup with higher voltage output compared with MFC-I. Moreover, the maximum power density (23.8 W/m^3) of MFC-S was approximately one quarter higher than that of MFC-I (19.1 W/m^3) due to the structure-induced better mass transfer of staggered array. No noticeable difference in anodic current maldistribution between the two MFCs was observed at a similar cell current. For a batch feeding mode, compared with MFC-I, MFC-S had a slightly higher COD removal efficiency (84.3%) but much higher coulombic efficiency (82.3%) with a nonuniform segment CE distribution.

1. Introduction

Microbial fuel cell (MFC), using microorganism as catalysts to directly generate electricity from wastewater, is an economical pathway to a sustainable energy future [1]. Although experiencing a significant advancement in several key factors including electron transfer mechanisms [2], anode biofilm [3], electrode materials [4], process parameters [5], as well as MFC designs [1,6] recently, MFC technology still faces several challenges such as scale-up. Scale-up is an important consideration when MFC technology comes to practical application [6,7]. For MFC scale-up, there are several key factors such as the large reactor configuration, operation in a practical way, electrode performance, cost and longevity [6–8]. In large MFC, the long and uneven electrode spacing would lead to several undesired problems such as large internal resistance [6,7] and nonuniform current distribution [9]. Moreover, electrodes with suitable surface pretreatments, as the solid matrix for bacterial attachment and electrochemistry reaction, should provide large and matchable surface areas in the large reactor [6].

Unfortunately, most previous studies were conducted at lab-scale and the power density would significantly drop in the scale-up MFC system [6,8]. Previous studies reported that MFC power increases with the surface area of current-limiting electrode [6,10]. It is suggested that, for a specific-volume

* *Corresponding author*. Key Laboratory of Low-grade Energy Utilization Technologies and Systems, Chongqing University, Ministry of Education, Chongqing 40003, China. Tel./fax: +86 23 6510 2474.
E-mail address: zhuxun@cqu.edu.cn (X. Zhu).

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rector, the increasing surface area of electrode would improve the volumetric power density. Thus, packed bed or multi-electrode structure is usually used as MFC electrodes due to the high specific surface area. Compared with packed bed, multi-electrode structure would be a more suitable choice as the lower contact resistance and easier arrangement for design [11]. However, few studies of MFCs with multi-electrode have been reported recently. Previous study showed that, in MFC scale-up process, the maximum power density of a larger MFC (15 W/m^3, 520 ml) using 4 brush anodes was slightly higher than that of a small MFC (14 W/m^3, 28 ml) with carbon paper as the anode [6]. More recently, Jiang et al. [12] reported that MFC power density was improved by 2.2 times using a 4-anodes/cathodes structure instead of using a single-anode/cathode. With the idea of increasing electrode numbers, they developed a MFC with 12-anodes/cathodes in the pilot-scale (20 L) and achieved a further improvement of the power density [13]. Besides, a relatively high power density (over 40 W/m^3) was achieved by constructing a multi-electrode MFC with horizontal liquid flow [14]. Ahn et al. [11] reported that a multi-electrode continuous flow microbial fuel cell with separator electrode assembly design was constructed to obtain stable current and can be used for treating actual wastewater. Gardel et al. [15] investigated how duty cycling influenced cumulative charge, current and microbial composition by using a 15-anode environmental MFC. Obviously, a multi-electrode structure is attracting more attention for MFC scale-up.

In a specific MFC chamber, the more tenuous electrodes are used, the more electrodes can be integrated and then the larger electrode surface area would be obtained, showing an attractive application to future large MFCs [9]. However, it is inevitable to consider the key design factors when the number of electrodes increases to a certain amount in MFC scale-up process. Liu et al. [6] reported that the power of single-chamber MFC increased by 36% after switching the anode electrode orientation from parallel to perpendicular, which was mainly due to the reduced electrode spacing. This suggests that the electrode spacing is an important factor in MFC scale-up. Besides, mass transfer is another important consideration in the design of large MFC with multiple electrodes. Previous studies have reported that mass transfer would significantly affect MFC power generation. Nielsen et al. [16] reported that a 4-fold increase in the power density was observed in a benthic MFC when the mass transfer was enhanced by mixing the fluids in the anode. Cheng et al. [17] showed a significant increase in power generation of a continuous flow MFC when the anolyte flowed through the porous carbon cloth anode. It was demonstrated the flow over multiple anodes would influence the substrate concentration, further affect the performance of MFC with air cathode [11].

Therefore, considering mass transfer factor, how to arrange the electrodes is an important consideration for large MFC design when the electrodes increase to a large amount. Generally, the orderly arrangement for the array usually contains staggered array, inline array and the combined array. It is known that, in the downstream rows, the mass transfer from the main flow area to the surface of cylinder is strongly influenced by the array pattern [18]. Compared with the inline array, the staggered array gives a better mass transfer to the cylinder surface as the structure-induced fluid disturbance under certain flow conditions [18,19]. Recent study reported that, by using Lattice Boltzmann simulation, the structure-induced fluid disturbance in the flow and concentration fields of substrate solution would significantly enhance the mass transfer to the surface of staggered tube bundle and further improve the biodegradation in a biohydrogen production system [19]. This effect may be similar to the MFC with graphite rod arrays. Thus, it is expected that the electrode array pattern would influence the flow and concentration fields of substrate and then impact on the performance in a continuous flow multi-electrode MFC.

In this study, two liter-scale MFCs with staggered electrode array (MFC-S) and inline electrode array (MFC-I) were constructed using tenuous graphite rods as the electrodes. The objective of the present study was to investigate the effect of anode electrode array pattern on the MFC start-up process, power generation, current distribution, COD removal and coulombic efficiency distribution.

2. Materials and methods

2.1. MFC construction

As shown in Fig. 1, the liter-scale MFCs with electrode arrays were constructed by two chambers using polyacrylic plastic with 1.87 L in volume separated by 90 × 90 mm proton exchange membrane (PEM) (Nafion 117, Dupont). Both the anode and cathode chambers were evenly filled with 225 graphite rods ($\Phi = 2.4$ mm, $L = 140$ mm, Xingyuan, China) in staggered arrangement (MFC-S) and inline arrangement (MFC-I), respectively, serving as the electrodes. Each rod with an immersion length of 110 mm in the electrolyte had a surface area of 8.29 cm^2 for bio-electrochemistry reaction. The anode electrode was divided into 9 segments numbered sequentially as A, B and C rows based on the distance to the cathode and as 1, 2 and 3 lines based on the flow direction of the anolyte. The entire electrodes in cathode were together used as the cathode current collector. To measure the segment current individually, the wire from each anode segment was electrically isolated from each other and each anode segment was connected to the external resistance box through a small fixed resistance (1 Ω). To maintain uniform flow, a liquid distributor was installed at the inlet of the chamber. Two Ag/AgCl reference electrodes were placed in the anode and cathode compartments.

2.2. MFC operation

The MFC-S and MFC-I were simultaneously inoculated with the effluent from a running MFC fed with an artificial wastewater with sodium acetate (500 mg COD/L; solution conductivity, ionic strength = 15.12 mS/cm) as previously reported [3]. After a successful startup, the anode was fed with the fresh wastewater. The cathode was continuously supplied with 50 mM potassium ferricyanide solution to minimize its influence on the whole cell performance. Both the anode and cathode compartments were operated in a continuous flow mode at a flow rate of 5 ml/min. In the test of COD removal,