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Enhancing power generation of scale-up microbial fuel cells by optimizing the leading-out terminal of anode

Shaoan Cheng*, Yaoli Ye, Weijun Ding, Bin Pan

State Key Laboratory of Clean Energy Utilization, Department of Energy Engineering, Zhejiang University, Hangzhou 310027, PR China

HIGHLIGHTS

- A simple model to simulate the power loss of scale up microbial fuel cell.
- Leading-out terminal could result in more than 47.1% of power loss.
- Leading-out terminal of anode is one of the key factors for scaling up MFC.

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ABSTRACT

Low power output and high cost are two major challenges for scaling up microbial fuel cell (MFC). The ohmic resistance of anode increasing as MFCs scale up can be one of main reasons for power density decrease. We present a simple model to simulate power loss and potential drop distribution caused by ohmic resistance of carbon mesh anodes with different dimensions and various leading-out terminals. We also conduct experiments to confirm the simulation work and the large impact of anode ohmic resistance on large-scale MFCs by varying leading-out configurations. The simulation results show that the power loss with an anode size of 1 m^2 can be as high as 4.19 W at current density of 3 A m^{-2}, and the power loss can be decreased to 0.04 W with optimized configuration of leading-out terminals and to 0.01 W by utilizing brass mesh as anode material. The experiments well confirm the simulation results with the deviations less than 11.0%. Furthermore, the experiment results also show that more than 47.1% of the power loss from small-scale to large-scale MFC comes from bad-leading-out terminal. These results demonstrate that leading-out terminal of anode is one of the key factors for scaling up MFC.

1. Introduction

Microbial fuel cells are devices that generate electricity from oxidation of organic compounds with microbes as catalyst. MFC holds great potential to become a sustainable way of extracting energy from wastewater and doing wastewater treatment simultaneously. Different configurations of MFCs have been tested, such as tubular [1], flat plate [2], upflow [3], downflow [4], two-chamber and single-chamber [5], cloth electrode assemblies (CEA) [6] and spiral wound [7]. In all variety of configurations, single-chamber air-cathode MFCs may be the fittest candidate for scaling up for its relatively low cost, simple and compact structure, and high power output. The carbon based materials, with qualities as conductivity, biocompatibility and chemical stability, are mostly used as anode in MFC, such as carbon cloth [8], carbon fiber felt [9], carbon fiber brush [10], carbon mesh [11]. However, carbon cloth and carbon felt have relatively high cost, and may not suit for scale-up MFC. Carbon brush has low cost and high surface area, but it is unable to be used to construct a compact structure for high volumetric power density of MFC. Carbon mesh, with low cost and showing good performance in compact MFCs, could be an alternative anode material for scale-up MFC. Aside from carbon mesh, metal mesh is another alternative to be anode material for its super conductivity, but metal mesh has low surface area and bad biocompatibility [12]. Up to now, in laboratory scale (less than 30 mL), the maximum area power density of MFCs (power normalized to the electrode surface area) has reached 6860 mW m^{-2} (2.62 mA cm^{-2}, 12 mL) through adjustment of cathode/anode area ratio [8]; the maximum volumetric power density (power normalized to the volume) of 1.55 kW m^{-3} (0.99 mA cm^{-2}, 2.5 mL) has been achieved by reducing electrode spacing in pH9 bicarbonate buffer [13]. The power density achieved in small-scale MFCs under optimized conditions indicates that it is feasible to scale up MFC for practical application in terms of power generation if the power density can be maintained.

* Corresponding author. Tel.: +86 571 87952038; fax: +86 571 87951616.
E-mail address: shaoancheng@zju.edu.cn (S. Cheng).

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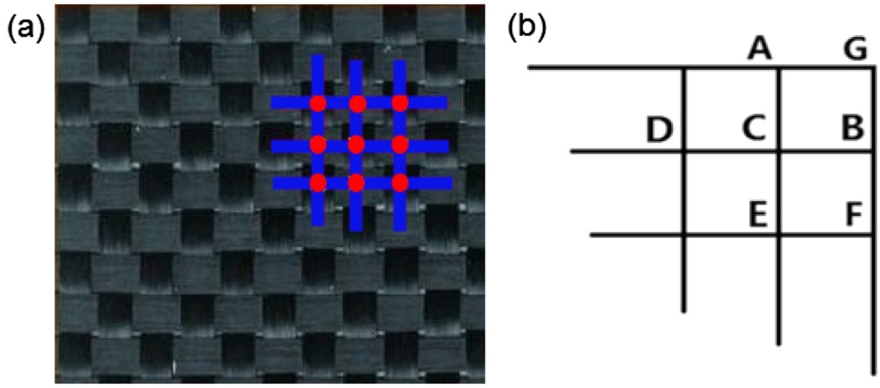

Fig. 1. A photograph of carbon mesh (a); simplified model for calculation (b).

There are two main approaches for scaling up MFC: increasing individual dimension of each cell and connecting several MFCs to form a stack system [14]. High performance of large-dimension MFCs is the prerequisite of high power-output stack system. Several investigations on large-scale MFC have been done. The single-chamber air-cathode MFC with a size of 520 mL was constructed and its volumetric power density was reported as 16 W m^{-3} [15]. The area power density reached 30 mW m^{-2} in the down-flow single-chamber MFC with a size of 850 mL [4] and 72 mW m^{-2} in a baffled MFC with volume of 1.5 L [16]. These results illustrate that scale-up MFCs perform much lower power density than small-scale MFCs, indicating that some factors certainly constrain the power output of scale-up MFCs. It has been found that power generation of MFCs is affected by pH, dissolved oxygen concentration, temperature, electrolyte, and species of bacteria resulting in the existence of ohmic, activation, concentration losses [17]. These factors had been well investigated in small-scale reactors [18–20] but less studied in scale-up MFCs. Cheng and Logan studied four MFCs with different sizes (28 mL, 250 mL, 1 L, 1.6 L) and found that anode performance was mainly affected by substrate concentration, while cathode performance was controlled by solution conductivity. They also explicitly pointed out that cathode specific area was the critical factor for high power density of scale-up MFCs [21]. The power density logarithmically decreased as the electrode size increased from 1.92 cm^2 to 155 cm^2, which indicated that power density generated by large-electrode MFCs could not be estimated by small-electrode MFCs [22]. Different from those results, recently Fan et al. reported a maximum volumetric power density of 2.87 kW m^{-3} (4.30 W m^{-2}, 16.4 A m^{-2}) with an effective anode surface area of 200 cm^2 by using double cloth-electrode-assemblies and u-shape current collector [23]. This volumetric power density is even higher than that of small-scale MFC (anode size 14 cm^2) [13]. This result may indicate that the leading-out terminals could be one of the critical factors for high power density of the scale-up MFC.

As anode dimension gets larger, ohmic resistance of anode becomes higher, because the distance between points where electrons generate and the leading-out terminal where current flows out of anode increases. This increase in the anode resistance may lead to a significant power loss of MFC. Thus, it is necessary to better understand this part of loss for scale-up MFC. In this paper, we setup a model to simulate the power loss and potential drop distribution on the carbon mesh anode with different configurations of leading-out terminal and various dimensions. We also conduct experiments to confirm the simulation results and to demonstrate that the leading-out terminal of anode has a critical effect on power output of large-scale MFC. The possible approaches to minimize power losses are also suggested.

2. Methods and experiment

2.1. Model and calculation

To simplify calculation, seven basic assumptions made for developing the model are that (Fig. 1(a)): 1) two paralleled adjacent bundles of carbon fiber are assumed not in touch with each other; 2) contact resistance between mutually orthogonal carbon fibers is negligible; 3) the carbon mesh has uniform physical properties; 4) bundles of carbon fiber are represented as lines with same length but width ignored; 5) microbes evenly grows on the carbon mesh anode, which results in even distribution of current input; 6) current with equal value was input only into each node; 7) potential drop at the node or nodes leading out to external circuit is set to 0. The model for calculating the potential drop of the carbon mesh was represented as the mesh (Fig. 1(b)), where A, B, C, D, E, F, G were the nodes on anode simplified with assumptions. Based on Kirchhoff's Law, the sum of currents flowing into a node is equal to the sum of currents flowing out of the node. Thus, current input of any node in the mesh can be presented as follows:

The equation of the nodes at the corner of the mesh:

$$i_G^{\text{input}} = i_G^{\text{output}} = (U_G - U_A)/R_{\text{fibre}} + (U_G - U_B)/R_{\text{fibre}} \tag{1}$$

The equation of the nodes in the edge of the mesh:

$$\begin{aligned} i_B^{\text{input}} &= i_B^{\text{output}} \\ &= (U_B - U_G)/R_{\text{fibre}} + (U_B - U_F)/R_{\text{fibre}} + (U_B - U_C)/R_{\text{fibre}} \end{aligned} \tag{2}$$

The equation of the nodes in the middle:

$$\begin{aligned} i_C^{\text{input}} &= i_C^{\text{output}} \\ &= (U_C - U_A)/R_{\text{fibre}} + (U_C - U_B)/R_{\text{fibre}} + (U_C - U_E)/R_{\text{fibre}} \\ &\quad + (U_C - U_D)/R_{\text{fibre}} \end{aligned} \tag{3}$$

The equation of the node connecting to external circuit:

$$\begin{aligned} U &= 0 \\ i^{\text{input}} &= 0 \end{aligned} \tag{4}$$

In this approach, an equation is established for each node in the mesh, where U represents potential drop of a node, i the sum of currents that flow in or out of a node and R_{fiber} the resistance between two adjacent nodes. As the number of equations equals to the amount of variables, unique solution for the potential drop of