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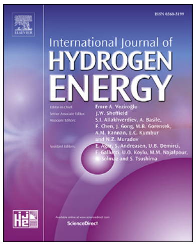

Response of stacked microbial fuel cells with serpentine flow fields to variable operating conditions

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ABSTRACT

The stacked microbial fuel cell (MFC) is a potential pathway for future applications, and its response to variable operating conditions is important for practical operation. In this study, a stacked MFC with serpentine flow field was constructed to investigate the stack performance and response to cell number, connection type, variable loads and electrolyte flow rates. The results showed that the highest maximal power (22.2 mW) was observed in a series connection, which was 12.1% and 29.1% higher than the maximal power in the parallel and hybrid connection, respectively. With the increasing number of cells, a gradually decreasing increase in the voltage output was found in the parallel stack and series stack at a high load, while the series stack showed first an increase and later a decrease in the voltage output at low load. Voltage reversal was observed when switching to a series connection or decreasing the load, resulting in a decreased stack voltage. The performance of the stack could be improved to an extent by increasing the electrolyte flow rates.

Introduction

Microbial fuel cells (MFCs), which uses electrochemically active bacteria (EAB) as catalysts to directly generate electricity from wastewater, is a potential pathway to a sustainable energy future [1,2]. Although there has been significant development in biofilm enrichment [3,4], reactor configuration [5,6], separator [7,8], electrode materials [4,9], mass transfer [3,10,11] and the optimization of process parameters [3,12], the power output of MFCs remains insufficient for practical applications. For an individual MFC, the working voltage is usually below 0.5 V, resulting from the thermodynamic and kinetic constraints [1]. To fulfill the real application requirements, many individual MFCs could be connected in parallel, series and hybrid stacks to promote the current, voltage and power [13–15].

In the past decade, most studies of stacked MFCs were conducted on voltage reversal and configuration. It was found that charge reversal could lead to the reverse polarity of cells and a loss of power generation in the MFC series stack [13]. Various electronic components such as capacitors and DC/DC

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voltage boosters, have been used to alleviate this phenomenon to a certain extent and to further promote the power [14–16]. In addition, it was demonstrated that using the maximum power point tracking devices and hybrid connectivity, an increased power output and voltage reversal avoidance in series connected MFC stacks can be achieved [17]. With respect to the new configuration, several novel stacked MFCs were studied recently. Liter-scale baffled stacking microbial fuel cells were used to generate electricity and treat wastewater containing sulfide and high strength molasses [18,19]. A 10-liter serpentine-type MFC stack constructed with PVC (polyvinylchloride) pipe was developed to treat brewery wastewater [20]. A continuous microbial fuel cell stack with a dual gas diffusion cathode design was developed to treat dark fermentation effluent [21]. A hybrid microbial fuel cell stack based on single and double chamber MFCs was proposed for self-sustaining pH control [22]. Interestingly, untreated urine was used for power generation in a miniature microbial fuel cell stack [23]. Obviously, for future application, more attention should be paid to MFC stacks.

A further important consideration for MFC stacks is their response to changes during operation. In future practical application, the MFC stack is used to power multiple devices with varied electric properties and it is necessary to switch the operation modes [24]. Compared with other fuel cells, MFCs had a relatively slow response due to the slow bioelectrochemical reaction [25]. It is well known that the architecture of the biofilm adapts in response to environmental stresses, such as low nutrient availability, high shear forces, unfavorable pH and toxic compounds [3]. In addition to environmental impacts, MFCs also need to adapt in response to the changes of operation in future practical applications. Several MFC studies reported the dynamic behavior in terms of variations in cells or changes in operating conditions and parameters. Katuri and Scott reported a dynamic response of MFC using membrane electrode assemblies design to the external resistance and COD changes, and a corresponding model was developed [25]. Yuan et al. investigated the responses of electrochemical characteristics and performance of anodic biofilms to pH changes in MFCs [26]. For MFC-based sensors, it is significantly important to investigate the dynamic response time and sensitivity after a change of operating parameters [12,27–30]. In addition, a dynamic model was developed to simulate the transient response of MFC voltage to the current step-change [31]. With respect to an MFC stack, few related research was investigated on the response to the variable operating conditions, which is insufficient for future practical operation. It was reported that a MFC stack fed with glycerol was tested to investigate the effects of connection modes on the electricity generation and microbial community [24]. Dynamic reconfiguration as a designing energy harvesting circuitry for MFC stacks can reduce the charging times by allowing storage of the same amount of energy in a shorter period of time [32]. However, more research should be focused on the dynamic response of MFC stack to other key variable operating conditions, proving better understanding of MFC stack operation.

In this study, serpentine flow fields were used to enhance mass transfer and four flat plate MFCs with serpentine flow fields were constructed into a stack in parallel, series and hybrid connection. The objective of the present study was to investigate the response of the stacked MFC to cell number, connection type, variable loads and electrolytes flow rates.

Materials and methods

MFC stack configuration and inoculation

In this experiment, the stacked microbial fuel cell with serpentine flow fields was conducted using four identical MFC units, as shown in Fig. 1(a) and (b). Each MFC consisted of a proton exchange membrane (PEM) (Nafion 117, DuPont), two carbon cloth electrodes (E-TEK, B-1A, America) and Plexiglass plates with a serpentine flow channel holding a volume of 2.7 ml. The PEM and electrodes had an apparent surface area of 25 cm^2. Both anode and cathode compartments were equipped with Ag/AgCl reference electrodes.

For each individual MFC, the anode compartment was inoculated with the effluent from a running MFC fed with an artificial wastewater. And the running MFC was previously inoculated using the activated sludge from the primary clarifier of Tangjiatuo Wastewater Treatment Plant of Chongqing. The artificial wastewater contained 2.7 g/L CH_3COONa, 6 g/L Na_2HPO_4, 3 g/L KH_2PO_4, 0.1 g g/L NH_4Cl, 0.5 g/L NaCl, 0.1 g/L $MgSO_4 \cdot 7H_2O$, 15 mg/L $CaCl_2 \cdot 2H_2O$ and 1.0 mL/L of a trace elements solution (500 COD mg/L; pH: 7.04; Conductivity: 15.12 mS/cm). A 50 mM potassium ferricyanide solution was used as the catholyte. The flow rates of each anode and cathode were 1.0 ml/min, unless otherwise noted. After inoculation, the four MFCs were constructed into stacks in parallel, hybrid or series connections for the tests. During the stack test, the stack was operated at different connection modes as shown in Fig. 1(c). All the tests were conducted in a temperature-controlled room at 25 °C.

Measurements and calculations

Stack and cell voltages (U), anode and cathode potentials, of each MFC were collected every 15 s via an Agilent 34970A data acquisition unit connected to a PC. In the polarization test, the external resistance varied in a range of $5–1.0 \times 10^4\ \Omega$ to control discharging and to record the voltage–current curves. After each change in the external resistance, the MFCs were held until the current and cell voltage reached steady-state with a voltage drift of less than 5 mV/h. The stack current (I) is equal to the voltage divided by the external load and the power (P) is the product of the voltage and the current.

Results and discussion

Stacked MFC performance under different connection types

To increase the overall stack voltage or current, the four individual MFCs were operated in parallel, series and hybrid connections. As shown in Fig. 2, this resulted in an open circuit potential (OCP) of 3.27 V for the series connection and 1.64 V for the hybrid connection, which was much higher than the OCP (0.82 V) of the parallel connection. With respect to the

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