World Applied Sciences Journal 31 (12): 2051-2056, 2014
ISSN 1818-4952

DOI: 10.5829/idosi.wasj.2014.31.12.649

# Power Generation in a Cascade of Five Hydraulically and Electrically Connected Microbial Fuel Cells

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**Abstract:** In this paper bioelectricity production for more than 20 days in a two-chambered microbial fuel cell (MFC) packed with granule activated carbon (GAC) was investigated. The system consisted of five individual MFC units that were hydraulically connected by feed flow and electrically connected either in series or parallel and operated in continuous mode. Glucose as substrate with a concentration of 1 g/l and anaerobic sludge were used for power generation. 400 µM of potassium permanganate was used in the cathode chambers as an electron acceptor. The maximum power density generated in the MFC was 989.70 $mW/m^3$, with respect to the net liquid volume of the anode chambers (0.00015 $m^3$).

**Key words:** Bioelectricity production · Continuous mode · Granule activated carbon (GAC) · Microbial fuel cell · Potassium permanganate

## INTRODUCTION

Since fossil fuels are finite and their consumption causes environmental pollution, scientists have been encouraged to explore economically and environmental-friendly alternative sources of energy in recent years [1]. One of the renewable and environmental-friendly sources of energy is the fuel cell (FC). Inorganic fuel cells have gained a lot of attention in recent years and reached an advanced state in their development, however these FCs need expensive and rare metal catalysts [2]. Biological fuel cells (BFCs) are a kind of FC that convert chemical energy into electricity via biochemical pathways and employ biocatalysts instead of metal ones. BFCs are classified according to their biocatalysts. Enzymatic fuel cells (EFCs) use isolated enzymes, while microbial fuel cells (MFCs) use the whole organisms. MFCs usually consist of an anode chamber and a cathode chamber separated by a membrane. Oxidation of substrate in the anode chamber produces electrons and protons that are transferred to the cathode. In the cathode chamber, reduction reaction occurs among the electrons, protons and electron acceptor ($O_2$) and produces $H_2O$ [3].

The main challenges for practical applications of MFCs are difficulties in the scaling up process and the high material costs. Anodic materials present an important parameter in capital cost and performance of MFCs [4]. Among different anodic materials, three-dimensional anodic materials are cost-effective. These materials increase the surface area and therefore improve the power density [5-10]. Several three-dimensional anodic materials have been tested such as granular graphite, granular semicoke, granular activated carbon (GAC), graphite felt, carbon felt and graphite wool and among them, GAC had an acceptable performance [5, 7].

Since the batch process has some disadvantages such as substrate depletion and low power generation, most of the researches are aimed to investigate continuous systems for bioelectricity generation and wastewater treatment [11].

Produced power from single MFCs is not suitable for real applications. In order to increase the voltage or current, MFCs can be stacked together (i.e., linked together in series or/and parallel). Connecting MFCs in parallel mode adds the currents, while the voltage is the same for all MFCs On the other hand, connecting MFCs

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in series mode adds the voltages and the current is the same for all MFC units [11-17]. It should be mentioned that stacking a number of MFCs together in series mode can result in voltage reversal [17].

The main objective of this research was to produce bioelectricity from Artificial Waste (AW) as fuel in a MFC in continuous mode. Five individual two-chambered MFCs were connected either in series or parallel circuit mode and the overall performance was investigated in terms of bioelectricity production. In order to improve the reduction reaction, potassium permanganate as an electron acceptor was used in the cathode chambers. Irregular GAC was used as the anode electrodes. Long term performance of the fabricated MFC was also reported.

## MATERIALS AND METHODS

**Experimental Set-Up:** The MFC used in this study consisted of five individual two-chambered MFC units. The anodes of five cells were connected sequentially via a 1 cm diameter hole. Each individual cell was fabricated from Plexiglas material (4 × 4 × 5 cm). All cathode chambers had two ports on the top, one for the electrode terminal and the other one for air pump. The anode chambers had just one port for the electrode terminal. In each cell, a GORE-TEX cloth with a sectional area of 4 $cm^2$ (2 × 2 cm) was used for the separation of two chambers. The membrane pretreatment steps were boiling for 1 h in 0.1 M $H_2So_4$, washing with deionized water, then boiling for 1 h in 11.11% $H_2O_2$, washing with deionized water and finally boiling for 1 h in deionized water. Unpolished graphite sheets (2 × 2 × 0.5 cm) were used as the cathode electrodes and fixed next to the membranes at a distance of 1 cm by copper wire (0.09 mm). An aquarium air pump (model Aco-5505 Guangdong Hailea, China) was used in the cathode chambers in order to supply oxygen. The anode chambers were filled by irregular GAC (2 - 5 mm in diameter). Unpolished graphite sheets (2 × 2 × 0.5 cm) connected to the copper wire were used to gather electrons flowing in the anode chambers. The net liquid volume of each anode chamber was 30 ml due to GAC adding. Figure 1 shows the schematic representation of the fabricated set-up.

**Operational Condition:** The anodes of the MFC were inoculated with anaerobic sludge collected from the dairy wastewater treatment plant, Tehran, Iran. The growth synthetic media contained the following components (per liter): 1000 mg glucose, 0.114 mg of urea, 0.046 mg of $K_2HPO_4$, 0.4 mg of $FeCl_3$, 3 mg of $MgSO_4$, 0.11 mg of $CuSO_4.5H_2O$, 0.7 mg of NaCl, 0.015 mg of $ZnCl_2$, 4 mg of $Na_2S_2O_5$, 0.254 mg of $MnSO_4$ and 2.06 mg of $FeSO_4.7H_2O$. In each cell, 20 ml of the growth media and 10 ml of the filtered sludge were used as the anode solution.

Potassium permanganate (400 μM) was used in the cathode chambers [18]. Five cells were connected electrically either in series or parallel. For electrical connection in series mode, the cathode of the first cell was connected to the anode of the next cell by copper wire and the completed circuit was loaded with a 1 KΩ external resistor. In parallel mode, the common anodes and common cathodes were connected with a 1 K? external resistor. All five cells were hydraulically connected and shared the same feeding and discharging port. In continuous mode, a peristaltic pump (THOMAS, Germany) was used to control the flow. A flow rate of 0.5 ml/min corresponding to an organic loading rate (OLR) of 4.8 gCOD/ld, which ensured the substrate sufficiency, was selected for the experiments. The total cascade hydraulic retention time (HRT) was 5 h and it was measured from the volume of the medium and the flow rate into the reactor. All chemicals used for the experiments were analytical grades and supplied by Merck (Germany). All experiments were carried out at room temperature (20 ± 2°).

**Calculation and Analysis:** Voltage was monitored using a digital multimeter (model 5000a Sanwa, Japan) and a data acquisition system every 30 min. The polarimetry technique was used to analyze the MFC performance under different electrical configurations. Polarization data were produced by changing resistor values over the range 1 M to 50 Ω and measuring the corresponding voltage. After changing each external resistance, it takes 5 - 30 min for the voltage to reach a constant value. Current density (I, $mA/m^3$) and power density (P, $mW/m^3$) were calculated using the following equations:

$$I = V / Ru \quad (1)$$

$$P = V^2 / Ru \quad (2)$$

where V is the measured voltage in mile volts (mV), R is the external resistance in ohms (Ω) and ◎◎ is the net liquid volume of the anode chambers (0.00015 $m^3$) in cubic meters ($m^3$).

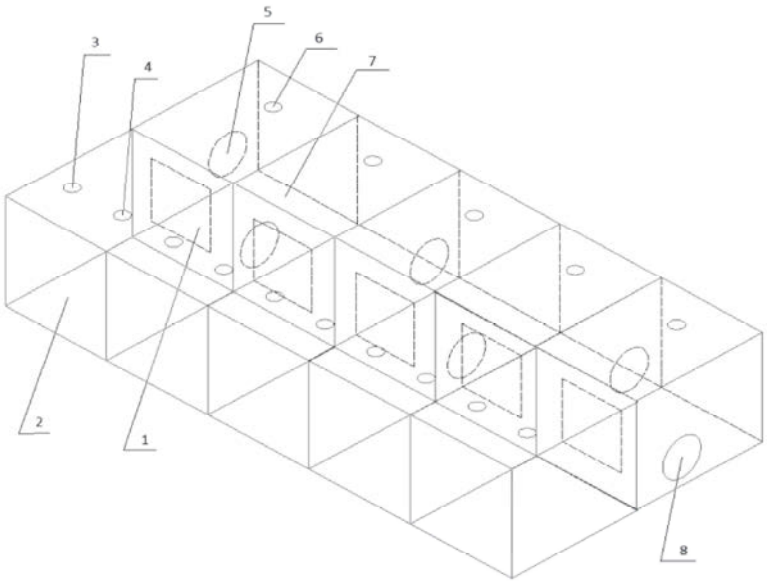


Fig. 1: Schematic representation of the self-designed MFC. 1-membrane; 2-cathode chamber; 3-electrode terminal; 4-sampling port; 5-inlet; 6-electrode terminal; 7-anode chamber; 8-outlet

Internal resistances ($R_{int}$) were calculated from the slope of the polarization curve using the following equation [19]:

$$V = E_{cell} - IR_{int} \quad (3)$$

where, $E_{cell}$ is the electromotive force of the cell.

## RESULTS AND DISCUSSION

When a stable voltage was established, the batch operation mode was switched over to continuous operation mode and prepared fuel was injected through the cells by means of a peristaltic pump. Five anode chambers were hydraulically connected by substrate flow, so all individual MFC units shared a common feed passage and discharge terminal. This design does not need an individual recirculation loop for feed and discharge, therefore the system is suitable for scale up and practical applications.

Hydraulically linking MFCs together would have some certain benefits such as large reduction in chemical oxygen demand (COD), increase in total voltage and integration of MFC with other wastewater treatment technologies [7].

**MFC in Parallel and Series Connection:** The system continuously operated with glucose (1 g/l) as substrate at OLR of 4.8 gCOD/ld. Figure 2 shows polarization and power density curves in parallel and series connection mode. In continuous operation mode, after 3 days the stable voltage was established. The polarization data were obtained at days 3, 13 and 23. Parallel MFC produced the maximum power density of 681.52 mW/m$^3$ (at 2863.5 mA/m$^3$) and at the end of the experiment (day 23) MFC produced the maximum power density of 376.20 mW/m$^3$ (at 1292.7 mA/m$^3$) which shows a 44.8% decrease in power generation. This reduction in power density was apparently due to the biofilm formation on the electrodes and membranes and an increase in the internal resistance (from 772 Ω at day 3 to 1300 Ω at day 23). Series MFC produced the maximum power density of 257.34 mW/m$^3$ (at 666.6 mA/m$^3$) and at the end of the experiment (day 23) MFC produced the maximum power density of 86.20 mW/m$^3$ (at 351.7 mA/m$^3$) which shows a 66.5% decrease in power generation. This number indicates more energy loss as a result of series connection mode. The main challenge in series connection mode is voltage reversal. Voltage reversal occurs due to the substrate starvation leading to different internal resistance and loss of bacterial activity [15]. In this study, high OLR (4.8 gCOD/ld) and high external resistances (1 KΩ) almost avoided the potential for voltage reversal [10]. However, energy loss observed in series connection mode is apparently caused by the lateral ion cross conduction effect which is not so important in parallel connection mode [13, 15, 20].

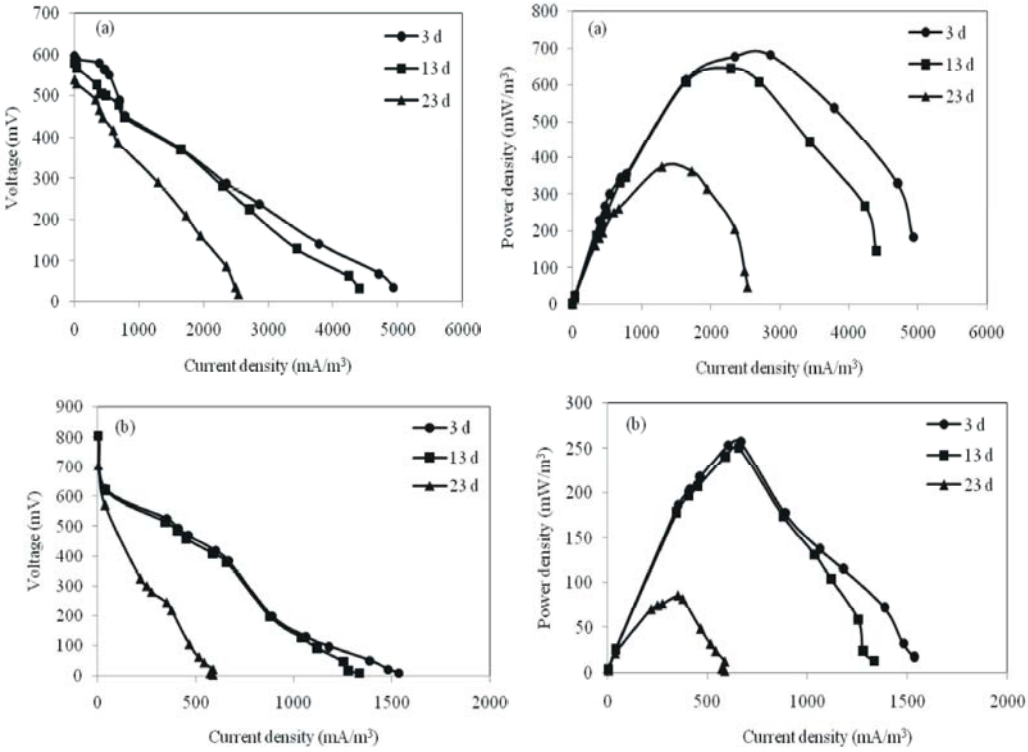


Fig. 2: Voltage and power density as a function of current density in parallel (a) and series (b) connection mode obtained on days 3, 13 and 23

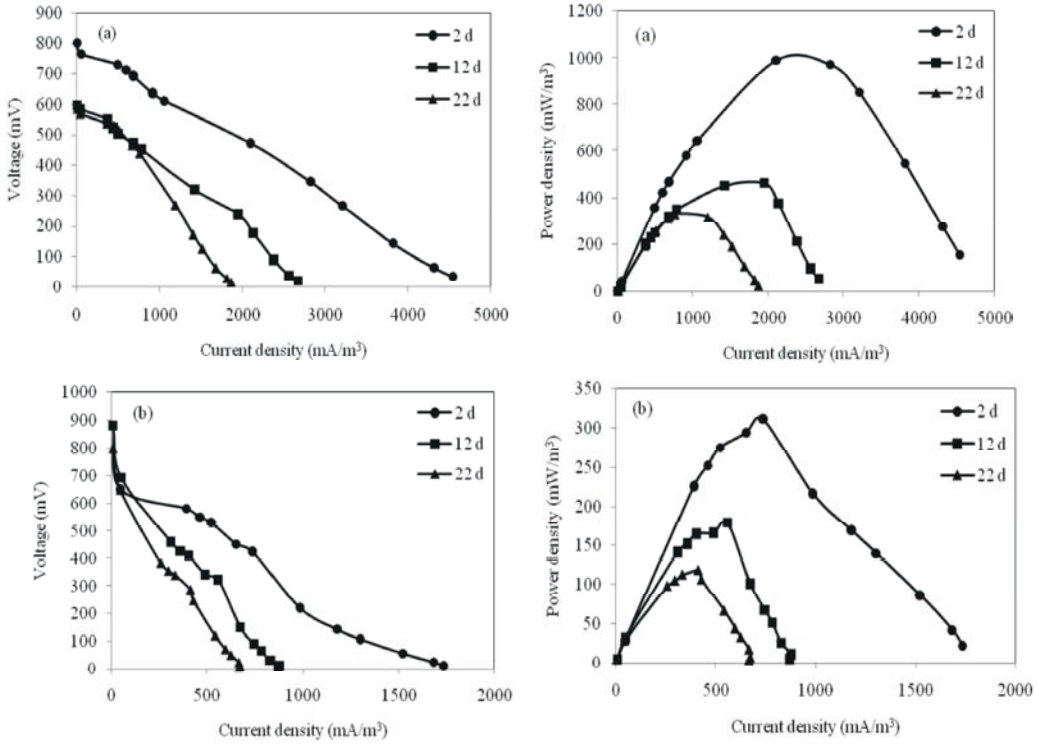


Fig. 3: Voltage and power density as a function of current density in parallel (a) and series (b) connection mode obtained on days 2, 12 and 22, with respect to 400 µM potassium permanganate

**Effect of Potassium Permanganate as an Electron Acceptor:** To improve reduction reaction, potassium permanganate (400 μM) as an electron receiver was used in the cathode chambers and a remarkable enhancement was observed in the electrical performance of the MFC [21]. In continuous operation mode, after 2 days the stable voltage was established. The polarization data were obtained at days 2, 12 and 22. Shorter start up time is due to the high redox potential of permanganate [22, 23]. Figure 3 shows polarization and power density curves in parallel and series connection mode, with respect to 400 μM potassium permanganate. The parallel MFC generated the maximum power density of 989.70 mW/m$^3$ (at 2096.7 mA/m$^3$) and for the series MFC the maximum power density was 312.00 mW/m$^3$ (at 734.0 mA/m$^3$), respectively. It was found that in the case of using permanganate, the decrease in power density in the first 10 days is more significant. This observation is due to the permanganate depletion.

Lorenzo *et al*., (2010) established a single-chambered MFC packed with granular graphite and operated it with a flow rate ranging from 0.03 to 1 ml/min. The MFC produced 1.3 W/m$^3$ of power density, with respect to the net anodic volume (12.5 cm$^2$). In an experiment by Zhuang and Zhou (2009) in a single-chambered MFC which shared a common feed passage, the maximum power density of 1.2 W/m$^3$ was achieved. The MFC operated with a flow rate of 1.04 ml/min. These results are almost comparable to that observed in this study (989.70 mW/m$^3$), considering the fact that single-chambered MFCs usually produce more power density than two-chambered MFCs.

It should be mentioned that addition of GAC to the anode chambers enhanced the anodes surface area which is favorable for the attachment and growth of the electrogenic bacteria. *Geobacter* is the most populous group in the GAC-packed MFCs [5, 6].

## CONCLUSION

This study demonstrates the use of a two-chambered scalable MFC to produce electricity from pure glucose. Potassium permanganate (400 μM) was used in the cathode chambers in order to improve the MFC performance. Five MFC units were connected either in series or parallel circuit mode. Series connection mode showed energy losses due to the lateral ion cross conduction effect. Parallel connection mode is preferred, since most of the electrical devices need a high current rather than voltage. The maximum power density and current density at the maximum power density in parallel connection mode (400 μM potassium permanganate) were 989.70 mW/m$^3$ and 2096.7 mA/m$^3$, respectively. Fabricated MFC is cost-effective and in order to achieve desirable voltage or current, individual cells can be easily added or removed. Obtained results indicate the feasibility of using a greater number of single MFCs for power generation.

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