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Research article

Domestic wastewater treatment and power generation in continuous flow air-cathode stacked microbial fuel cell: Effect of series and parallel configuration

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ABSTRACT

In this study, a continuous flow stack consisting of 40 individual air-cathode MFC units was used to determine the performance of stacked MFC during domestic wastewater treatment operated with unconnected individual MFC and in series and parallel configuration. The voltages obtained from individual MFC units were of 0.08–1.1 V at open circuit voltage, while in series connection, the maximum power and current density were 2500 mW/m^2 and 500 mA/m^2 (4.9 V), respectively. In parallel connection, the maximum power and current density was 5.8 mW/m^2 and 24 mA/m^2, respectively. When the cells were not connected to each other MFC unit, the main bacterial species found in the anode biofilms were *Bacillus* and *Lysinibacillus*. After switching from unconnected to series and parallel connections, the most abundant species in the stacked MFC were *Pseudomonas aeruginosa*, followed by different *Bacilli* classes. This study demonstrated that when the stacked MFC was switched from unconnected to series and parallel connections, the pollutants removal, performance electricity and microbial community changed significantly. Voltages drops were observed in the stacked MFC, which was mainly limited by the cathodes. These voltages loss indicated high resistances within the stacked MFC, generating a parasitic cross current.

1. Introduction

In recent years, the electricity production through microbial fuel cells (MFC) has aroused the interest of the scientific community as it has been seen as an emerging bioelectrochemical technology capable of producing electricity from an organic residue (Chaturvedi and Verma, 2016; Logan, 2012). A MFC is a device formed by an anode, a cathode, and a proton exchange membrane that produces electricity with the help of bacteria as catalysts, during the degradation of the organic matter present in the wastewater (Ahn and Logan, 2012; Logan, 2009). Currently, the studies on this technology are focused on finding a better architecture for its scaling, microbial communities and materials of the electrodes and separators (Butti et al., 2016; Ahn and Logan, 2012; Kim et al., 2012; Zhang et al., 2011; Jiang et al., 2010). In practice, the application of a MFC as a source of power is limited by the low voltage and electric current that is generated (0.8 V at open circuit voltage (OCV) and 0.6 V at closed circuit voltage (CCV) (Aelterman et al., 2006). It has been reported that when more than one individual MFC is connected in stack or multi-electrode, the voltage and current increase, depending on the connection mode (series or parallel) (Wu et al., 2016; Yazdi et al., 2015; An et al., 2014; Ieropoulos et al., 2013; Kim et al., 2013; Zhuang et al., 2012; Winfield et al., 2012; Dekker et al., 2009). Series and parallel connections in a stacked MFC are a key factor to consider for the scaling of the stacked MFC. The electricity production in a stacked MFC can be affected by several factors such as the configuration of the module, shared MFCs, un-shared MFCs, shared anolyte, external resistance, and microbial community (Kim et al., 2012; Katuri et al.,

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2011; Zhuang et al., 2009a,b; Wang and Han, 2009). Several studies have demonstrated that during the electricity production in different configurations of stacked MFC, voltage drops may occur due to the cathode limitations and to the phenomena on the ionic cross conduction (parasite current) and voltage reversal (An et al., 2015; Zhang and Angelidaki, 2012; Zhong et al., 2011; Zhuang and Zhou, 2009a,b; Rismani-Yazdi et al., 2008; Oh and Logan, 2007). Despite having reports on the operation of a stacked MFC, attention has not been paid to the changes of the bacterial communities formed on the anodic materials of MFC stacks. It is extremely important to identify the bacterial communities when the stacked MFC is operated at OCV, CCV, in series or parallel connection conditions.

There are several reports about the identification of the microbial communities formed in a single-chamber or two-chamber MFC unit (Jung and Regan, 2011; Logan, 2009; Debabov, 2008). Nevertheless, there are insufficient reports on the composition of microbial communities in a stacked MFC. Most bacterial species identified in an individual MFC that produce electricity are: *Geobacter sulfurreducens*, *Escherichia Coli,* and *Shewanella putrefaciens* (Eaktasang et al., 2016; Bond et al., 2012; Liu et al., 2012; Jung and Regan, 2011). The composition of the substrate (simple or complex), the operation mode of the cell (batch or continuous flow), the removal of organic matter, the configuration of the MFC (single-chamber or two-chamber), and the connection mode (series or parallel) may have an effect on the composition and dominance of microbial communities on the anode biofilms of a stacked MFC.

The change of connection can be decisive in the performance of the stacked MFC during the electricity production and the removal of organic matter (as chemical oxygen demand (COD)), because more complex interactions can exist in this type of systems compared to a single MFC, which operates separately. Kiely et al. (2011a,b) reported that microbial communities changed when a MFC and microbial electrolysis cell (MEC) were switched. Recently, Zhao et al. (2017) examined electricity production and microbial community in a stacked submersible MFC using glycerol as substrate. According to those results, it was reported that there are changes in the bacterial communities after switching the connection from parallel to series. The microbial community in one MFC unit was dominated by *Betaproteobacteria*, *Alphaproteobacteria*, *Thermomonas,* and *Flavobacteriia*. When the MFC units were connected in series and parallel modes, *Betaproteobacteria* and *Alphaproteobacteria* were the most dominant microbial communities. Aelterman et al. (2006) reported that the composition of microbial communities on anodic electrodes are more diverse in a two-chamber stacked MFC and that, when the stacked MFC's connection was switched from series to parallel, the microbial community did not change significantly. These authors reported differences on the diversity of microbial communities in different stacked MFC configurations and their studies were based on simple substrates such as glycerol and acetate, and they were limited to only a few units connected to each other (<20 MFC units). In this study, the performance electricity of a continuous flow air-cathode stacked MFC conformed by 40 MFC units was evaluated during domestic wastewater treatment, when the stack was operated unconnected at OCV, in series connection at CCV, and in parallel connection at CCV.

2. Material and methods

2.1. Stacked MFC construction and operation

The stacked MFC was assembled with nonconductive polycarbonate plate, which contained 40 units of air-cathode MFC in a shared reactor of 16 L. The reactor was divided into four modules of rectangular shape; each module was 70 cm high, 10 cm long, and 5.7 cm wide, it held 4 L of volume, and it contained ten single air-cathode MFC units (Fig. 1). Each individual MFC unit was composed by a carbon felt anode with a surface area of 0.0075 m^2. The anodes were connected externally by a single copper wire. A membrane electrode assembly (MEA) of 5 cm length and 5 cm width was exposed to air in each individual MFC unit and was utilized to separate the anodic chamber from the cathode. The MEA consisted of a cation-exchange membrane (CMI-7000, Membrane International Inc. USA) and a carbon cloth (Brunssen Inc. Mexico), which contained a PbO_2 layer of 0.5 mg/cm^2. Copper plates were used as electron collectors. The distance between anode and cathode was 2 cm and the distance between each MFC unit was 3 cm. The influent of the stacked MFC passed through MFC unit 1 and the effluent was collected from MFC unit 40, once it had passed through all MFC units. The stacked MFC was operated at shared anolyte mode (wastewater in the anodic chamber of the MFC), under continuous flow.

The anodic electrodes were inoculated with a mixture of 50% raw wastewater from residential housing and 50% of anaerobic granular sludge from a UASB reactor during 20 days, and then they were placed into the anodic chambers of the stacked MFC. Afterwards, the stacked MFC was operated at OCV during 4 months at a HRT of 3 d and fed with raw wastewater from residential housing. The chemical oxygen demand (COD) of the raw wastewater was 300 ± 50 mg/L and the ammonia nitrogen (NH_4-N) concentration was 28 ± 16 mg/L. Then, the stacked MFC was operated at a different external resistance of between 0.1 and 40 kΩ, using series and parallel connections. Therefore, the stacked MFC was operated under three operational conditions: 1) unconnected at open circuit voltage; 2) series connection at closed circuit voltage, and 3) parallel connection at closed circuit voltage.

2.2. Analysis and measurements

Real-time data of voltages, power density, and current density obtained from the stacked MFC were collected using a data acquisition system based on LabVIEW software, connected to a personal computer. The electricity produced by the system was monitored every 10 min. Current, I (mA), was calculated using $I=V/R_{ext}$, where V (mV) is the voltage and R_{ext} (Ω) is the external resistance. Power density, P (mW/m^2) and current density, j (mA/m^2), were calculated according to $P=IV/(A^*1000)$ and $j = V/(R_{ext}A)$, respectively, where A (m^2) is the surface area of the anode electrode. An electronic device was developed to measure the electricity produced in each individual MFC unit and during series and parallel connections. The change from one connection to the other one (individual unit, series, and parallel) was controlled from the computer. In order to measure the electricity at different external resistances (from 0.10 to 40 kΩ), the electronic device was coupled to a resistor portable box/load bank developed in-house. The change of the different external resistances was controlled from the computer.

COD and NH_4-N were evaluated in different sample points from the stacked MFC (influent, MFC 10, MFC 20, MFC 30 and MFC 40 (effluent) (Fig. 1). These parameters were analyzed using the Standard Methods (APHA, 2005).

2.3. DNA extraction

In order to determine the microbial communities on anode biofilms, biofilm samples were obtained from the anodes surface of different single MFC units. The anode biofilm samples were taken from MFC 1, MFC 10, MFC 20, MFC 30, and MFC 40. Biofilm samples were taken with a sterilized spatula and they were transferred aseptically to a sterile 12 mL-volume universal tube with 10 mL of