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On the staking of miniaturized air-breathing microbial fuel cells

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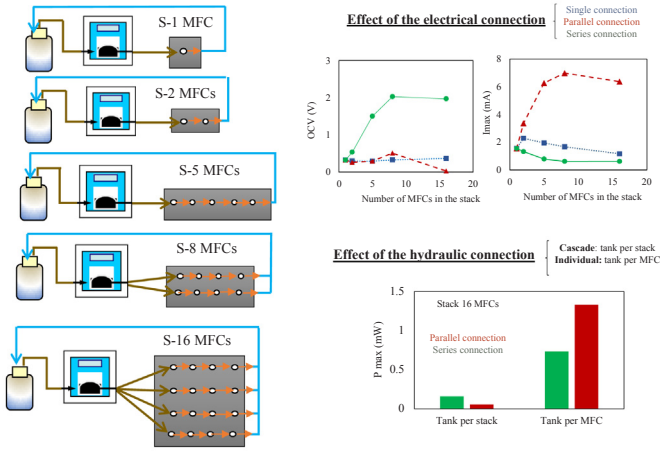
HIGHLIGHTS

- The higher the number of MFC in a stack, the higher the COD consumption.
- Electricity production is limited by the number of MFCs in the stack.
- Individual feeding tanks per MFC enhance the electricity generation.
- Series connection increases the voltage up to 6 times in the stack of 8 MFCs.
- Parallel connection increases the current up to 4 times in the stack of 8 MFCs.

GRAPHICAL ABSTRACT



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ABSTRACT

This work focuses on the scale-up of the MFCs by miniaturization and multiplication strategy. Performances of five stacks containing 1, 2, 5, 8 and 16 MFCs were compared. Each stack was evaluated under individual, parallel and series electrical connection as well as for cascade or individual hydraulic connection. Cascade feeding mode with a tank per stack favours the COD removal when the number of MFCs in the stack increases. However, despite operating without COD limitations, the energy production was disadvantaged. By changing the feeding system of a tank per stack into an individual tank per MFC, the performance of the whole stack enhances considerably. Stacking in series can increase the voltage 6 times while stacking in parallel can increase the current output about 4 times. For example, 8 MFCs can achieve 2.03 V connected in series and 6.98 mA connected in parallel. In addition, the power can be increased up to about 10 times leading to a power range high enough for real life applications.

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1. Introduction

Microbial fuel cells (MFCs) can help to recover part of the energy contained in wastewater, becoming an alternative renewable energy source [1]. Unfortunately, its practical application is limited because of the low power generated (50–200 W m^{-3}) and low working potentials (in a range of 0.3–0.5 V) achieved by single MFCs [2]. For this reason, scale-up of MFCs has received increasing attention during last years [3] and a great scientific effort has been focused on methodologies to get energy dense devices [4].

Scale-up by increasing the size of the MFC does not result in a proportional increase of the output energy and in the efficiency of the system, mainly because of the associated increase of the internal resistance [5] and the reduction of the electrode surface to volume ratio [6]. However, small MFCs result in higher energy recovery efficiencies [7]. By miniaturizing the MFC, shorting the electrodes spacing, increasing the surface-volume ratio and reducing the volume of the chambers, the typical parameters that influence the MFC performance (operational conditions and design parameters) could be better controlled [8]. Hence, the energy recovery could be enhanced by multiplying small MFCs leading to a new proposal of scaling-up, which is called 'miniaturization and multiplication of MFCś [9,10]. The miniaturization consists in reducing considerably the size of the MFC until building micro-chambers [11–13]. On the one hand, the miniaturization reduces the electrode spacing, on the other hand increases the surface-volume ratio. The combination of these factors allow to maximizes the feed flows into the biofilm, making easier the electron transference to the anode, lowering internal resistance and therefore improving the MFC efficiency [14]. As an example of laboratory scale-MFCs, a reported study shows that a projected anodic surface area of 2 cm^2 resulted in an impressive power of 3000 mW m^{-2} [15,16], whereas in another work with a projected anodic surface area much larger, 232 cm^2, the maximum power density reached only 26 mW m^{-2} [17]. Concerning to the volume, in the literature it has been showed that a MFCs operated with volumes of 6.3 or 29.6 mL resulted in very similar power densities of 0.44 and 0.38 W m^{-3}, respectively [18]. In the literature, it has been reported that the multiplication of MFC conforming stacks as scale-up strategy avoid energy losses ensuring at the same time higher efficiencies [18,19]. This process is named multiplication [9].

It is very important to multiply devices with very simply structure. Indeed, air-breathing MFCs are easier to arrange in a stack than double chambered MFCs and requires less space. Furthermore, air-cathodes guarantees no limitations in the availability of final electron acceptor [6]. For practical applications, the output energy can be increased by connecting electrically each single MFC assembled in the stack [9,10]. Serial connections lead to a potential equal to the sum of individual ones, while parallel connections increases the current output up to the sum of the currents exerted by each MFC [5,20]. However, these connections can produce contact potential losses and potential reversal due to imbalanced potentials caused by different reactions kinetics on the electrodes leading to erroneous operations, which worsen considerably the performances of the stack [21,22]. Zhao et al. developed a self-stacked submersible MFC, which degraded glycerol, obtaining the maximum current when connected in parallel (5.7 mA) and the maximum potential when connected in series (1.21 V) [21]. The maximum power density exerted was similar in both cases, around 450 mW m^{-2} [21]. Chouler et al. achieved 0.063 and 0.243 W m^{-3} arranging 3 MFCs in series and in parallel, respectively, while the power density reached by one unit was 0.053 W m^{-3} [9].

In addition to the electrical advantages obtained by the scaling up of MFC, the wastewater treatment capacity of these bio-electrogenic devices can be enhanced by connecting hydraulically each individual MFCs of the stack [23], which results in a cascade of MFCs where the outlet of the first MFC is the inlet of the second MFC and so on until the last MFC. The cascade reduces the bulk volume do not exposed to the electrodic surface area, increasing therefore the hydraulic retention time in the nearby of the electrodes [24]. In addition, it allows the MFC to operate with shorter diffusion distance leading to a more efficient volumetric electrode performance [24]. For example, Monasterio et al. achieved a further algal removal employing a cascade of 3D printed miniature air-cathode MFCs [25]. However, cascades of a large length could result in mass transfer limitations in the latter stages due to the operation at substrate concentrations near and even lower than the half saturation coefficient. This problem can be avoided by increasing the flow rate, which increases the loading rate of the system and the turbulence leading to a more uniform distribution of the substrate. Unfortunately, the higher the flow rate the higher the operational costs. Hence, scale up by miniaturization and multiplication seems to be a good choice for improving the performance of MFC, but further work has to be carried out in order to shed light on the way to optimize these devices. In addition, despite the number of publications related to stacking MFCs, most of them tested different electrical and hydraulic connections for a unique stack [21,26], being impossible to compare the results presented in these works.

In this context, the novelty of this work is the evaluation of the effect of electrical and hydraulic connections in a stack as well as the influence of increasing the number of MFCs configuring a stack over its electrical performance. The main aim in to enhance the voltage and the current exerted with the aim to use MFC in real applications. In order to reach this objective, five devices with different numbers of stacked MFCs (ranging from 1 to 16) were built up. In these set-ups, the influence of the electrical connection (series or parallel) as well as the hydraulic connection (individual feeding or cascade) were studied with the aim to understand and to deep into the stacking process with the number of MFCs.

2. Materials and methods

2.1. Experimental set-up

All the MFCs were build up with the same characteristics, size and materials. Each MFC consisted of a cathode opened to the atmosphere, which employed oxygen gas as final electron acceptor. The cathode was based on carbon paper (Freudenberg C2) with a 10% of Teflon and a load of 0.5 mg Pt cm^{-2} on its surface [27]. The face of the cathode not exposed to the air faced a Nafion N117 proton exchange membrane (DuPontTM Nafion PFSA Membrane). This membrane separated the anodic and the cathodic chambers. The anodic chamber had a free volume for the wastewater of 0.346 cm^3 and contained an anode made of carbon felt. Both, the anodic and the cathodic electrodes had an active area of 0.866 cm^2 and were connected externally by a resistance of 120 Ω. The distance between the electrodes and the membrane was reduced as much as possible to avoid high internal resistances. These individual MFC were used to configure stacks containing 1, 2, 5, 8 and 16 units and named S-1MFC, S-2MFCs, S-5MFCs, S-8MFCs and S-16MFCs respectively. A detailed scheme of the stack configurations is presented in Fig. 1.

2.2. Inoculation and operational procedure

The MFCs were inoculated with activated sludge obtained from the Wastewater Treatment Plant of Ciudad Real in Spain. More information about this facility can be found elsewhere [28]. This sludge underwent sedimentation to increase its biomass concentration. Once finished the sedimentation stage, 50% v/v of the settled sludge and 50% v/v of the supernatant (wastewater) was used to fill each auxiliary anodic reservoir tank. It was recirculated through the system for 24 h. Then, during the second and third days, 50% of the volume was daily removed and replaced by fresh sludge following the same operational pattern of the first day. At the fourth day and during the rest of the experiment, a sludge age of 2.5 days was established as operational