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Microbial fuel cells connected in series in a common electrolyte underperform: Understanding why and in what context such a set-up can be applied

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ABSTRACT

Microbial fuel cells (MFCs) have the outstanding ability to transform the chemical energy contained in organic matter directly to electrical energy. Unfortunately, they give only low cell voltage at maximum power. Connecting several MFCs electrically in series inside the same reactor may be a way to increase the cell voltage, but experimental attempts have shown poor efficiency for such single-electrolyte stacks.

The present study uses numerical modelling to understand the behaviour of single-electrolyte MFC stacks and to assess possible ways to improve it. The numerical model was validated by comparison with two experimental MFCs that produced 0.85 ± 0.05 mW each at 0.23 V cell voltage. Connected in series in a common electrolyte, the stack produced only 0.7 mW at 0.21 V, while, in theory, 1.7 mW could be reached at 0.47 V. The model showed that the drastic power loss was due to ionic short-circuiting, which may, however, be an interesting phenomenon to be exploited for designing an electro-microbial snorkel. The model also showed that decreasing the anode-cathode distance, increasing the distance between the MFCs or using baffles between them could optimize the single-electrolyte stack to produce up to 80% of the theoretical maximum power. Nevertheless, such designs are appropriate only for specific applications, e.g. biosensing. The model further suggests that benthic MFCs could be effectively connected in series.

1. Introduction

Microbial fuel cells (MFCs) have the outstanding capacity to transform the chemical energy contained in low-cost, renewable organic matter directly into electrical energy. Their global performance remains limited; 6.4 $W.m^{-2}$ has recently been claimed to be the highest power density supplied so far by a laboratory prototype [1]. Nevertheless, the low power supplied is not an unsurmountable obstacle for some future applications [2]. Actually, impressive demonstrations of the capacity of MFCs to satisfy the requirements of low-power-consuming devices started to be made more than a decade ago [3]. Various sensors and telecommunication systems have been powered by MFCs [4–6] and, in this framework, sediment MFCs have shown interesting capabilities [7–9]. Fun applications such as feeding a micro-robot with insect material [10] and powering a mobile phone with urine [11,12] have also helped to enlarge the possible application fields. Recently, an MFC designed as a "floating garden" that supplied LED-lights and a data transmission device [13] was presented at the 2015 Universal Exposition. Nevertheless, a few stumbling blocks still have to be overcome before the real potential of the technology can be clearly assessed. A major concern in MFC development is the low cell voltage that is produced when they operate at maximum power [9,14].

The cell voltage of a single MFC unit can be increased by using dedicated electronic harvesting systems [9,15,16] but a part of the power produced by the cell is consumed by the electronic power management system. Another option is to connect several individual MFCs electrically in series. In theory, the voltage provided by the MFC stack is the sum of the voltages of the individual cells but, in practice, tricky control problems arise [17]. As each MFC is allowed to evolve in its own way, the cells can drift to different behaviours, which often results in some MFCs working in electrolysis mode rather than power producing mode

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Glossary

Parameter

B	distance between the reactor wall and MFCs (cm)
d	anode-cathode distance (cm)
D	distance between MFCs (cm)
e	width between the baffles (cm)
E	Nernst potential (mV)
i_{max}	anodic maximum current (mA)
i_0	cathodic exchange current (mA)
K_M	substrate affinity constant (mol.L^{-1})
K_1, K_1	Kinetic parameters (–)
S	substrate concentration (mol.L^{-1})
U_{cell}	cell voltage (V)
W	reactor depth (cm)
α	charge transfer coefficient (–)
σ	electrolyte ionic conductivity (S.m^{-1})
φ	electrostatic potential (mV)

Subscript

A	Anode
C	Cathode
M	Electrode material
S	Solution

(voltage reversal) [18,19]. In practice, the cell voltage provided by MFC stacks can be much lower than the sum of the voltages of the individual cells. A power management unit must consequently be implemented to avoid voltage reversal and boost the stack towards the theoretical maximum power [20,21].

Immersing all the MFCs that are electrically connected in series in a common reactor may be an interesting way to mitigate the deviations of individual cells, as all the cells would thus be exposed to the same electrolyte under the same conditions. Moreover, a single-electrolyte reactor would allow compact devices to be designed, in which the risk of liquid leaks would be limited, maintenance simplified, and the MFCs supplied with fuel in an easier way than with individual cells. In spite of these obvious advantages, only a few experimental attempts concerning MFC stacks in a single reactor have been reported [22–24], likely because such a design has shown poor efficiency. Connecting several MFC units in series inside the same reactor has resulted in severe voltage loss. The voltage of the stack is generally considerably lower than the sum of the voltages of the individual cells. For example, four MFCs, each ensuring a cell voltage of 0.34 V, resulted in only 0.73 V when connected in series in the same reactor [23]. Similarly, four MFCs, each producing 6.5 W.m^{-3}, resulted in 14.7 W.m^{-3} [24]. The energy loss has been attributed to lateral ion cross-conduction between the cells [24], by analogy with what has been observed in arrays of chemical fuel cells [25]. Increasing the distance between the MFC units has been proposed to mitigate the voltage loss. For instance, when the distance between two MFC units was increased from 1 to 8 cm, the percentage voltage loss decreased from around 46.5% to 44% [22].

An intermediate way has consequently often been used by connecting individual MFCs through a hydraulic network. When the hydraulic connection is in parallel, the different MFCs are supplied with the same electrolyte and, when the hydraulic connection is in series, the different MFCs are supplied with almost the same electrolyte, if depletion of the substrate(s) and accumulation of metabolite(s) are not too important. Even in this case, the voltage of the MFCs connected in series is generally considerably lower than the sum of the voltages of the individual cells [22,26]. Seven miniature MFCs hydraulically linked produced ten times less current when electrically connected in series instead of parallel [27]. As observed with MFC units inside the same reactor, increasing the distance between MFCs has also been reported as a possible solution in this case [28]. The connection of individual MFCs through a hydraulic network was not considered here because the motion of the electrolyte through the different MFC cells consumes a lot of power, which limits the field of possible application types. In this context, the first self-sustained stack, achieved recently, required the connection of 40 MFC units to power the pump and the electronic control device [29]. The present study deals with the electrical connection of MFC units inside the same reactor without a hydraulic network.

As the problem is related to ionic conduction inside the stack, modelling the potential distribution should provide the most appropriate tool to address it in a comprehensive manner. The purpose of this work was to develop MFC numerical modelling to understand the cause of the voltage loss when several MFC units were set inside the same reactor, to determine whether some benefit may be gained, and in what conditions. With this objective, MFCs were designed with an abiotic air-cathode associated with a bioanode formed from compost leachate [30,31]. MFCs were fed with acetate, which was oxidized at the bioanode:

$$CH_3COO^- + 4H_2O \rightarrow 2HCO_3^- + 9H^+ + 8e^- \quad (1)$$

and oxygen was reduced at the cathode:

$$O_2 + 4e^- + 2H_2O \rightarrow 4OH^- \quad (2)$$

A numerical model was developed to map the electrostatic potential distribution inside the cells. The model was first validated by comparison with the experimental data and was then used to predict the performance of a single-electrolyte MFC stack by varying the architecture of the stack. The model allowed different stack architectures and large ranges of parameter values to be explored very fast so as to guide further experimental confirmation with the most appropriate designs and conditions.

2. Experimental

2.1. Microbial anode formation

Microbial anodes were first formed under constant applied potential in 650 mL 3-electrode set-ups. A carbon cloth (PaxiTech SAS, Grenoble, France) of 3×3 cm^2 geometric surface area connected to a platinum wire was used as the anode (working electrode), a platinum grid as the auxiliary electrode and a saturated calomel electrode as the reference (SCE, potential +0.24 V/SHE). A potential of −0.2 V/SCE [30,31] was applied using a VSP potentiostat (Bio-Logic SA, France). Current was recorded as a function of time (chronoamperometry, CA) and successive additions of sodium acetate 20 mM were made when the current fell to around zero. Reactors were kept in a heat chamber at 40 °C, which is the optimal temperature in the range from room temperature to 60 °C [32,33].

A leachate of garden compost was obtained by filtering a mix of 1.5 L of garden compost and 2.25 L of water, containing 60 mM KCl, through a cloth with a large mesh. This leachate served as both the culture medium and the inoculum for the first phase of the bioanode formation. Once oxidation peaks on CA indicated mature bioanodes (current around 15 mA), generally after 3 acetate additions, the compost leachate was replaced by a synthetic medium, which contained 50 mM bicarbonate buffer, 10 mL.L^{-1} macronutrients, 1 mL.L^{-1} micronutrients, 1 mL.L^{-1} vitamins, 4.5 g.L^{-1} KCl and 2.4 g.L^{-1} $NaH_2PO_4.H_2O$. pH was adjusted to 7.0. The aim