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Reducing start-up time and minimizing energy losses of Microbial Fuel Cells using Maximum Power Point Tracking strategy

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HIGHLIGHTS

- A Maximum Power Point Tracking system was studied to optimize MFC power generation.
- Pig wastewater was used as anode fuel to evaluate the system under real conditions.
- External load control decreased MFC start-up time of about one month.
- External load control increased Coulombic efficiency and decreased energy losses.

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ABSTRACT

Microbial Fuel Cells (MFCs) are considered to be an environmental friendly energy conversion technology. The main limitations that delay their industrialization include low current and power densities achievable and long start-up times. Maximum Power Point Tracking (MPPT) has been proposed as a method to enhance MFCs electrical performances. However, the specialized literature is still lacking of experimental works on scaled-up reactors and/or real wastewater utilization. This study evaluates the impact of a MPPT system applied to MFCs treating swine wastewater in terms of start-up time and long-term performance. For this purpose, two replicate cells were compared, one with applied MPPT control and one working with fixed resistance. Both MFCs were continuously fed with swine wastewater to validate the control system under real and dynamic conditions. The study demonstrated that the automatic resistance control was able to reduce the start-up time of about one month. Moreover, MPPT system increased of 40% the Coulombic efficiency at steady-state conditions, reduced energy losses associated with anode and cathode reactions and limited methanogenic activity in the anode chamber. A power density of 5.0 ± 0.2 W m^{-3} NAC was achieved feeding the system at an organic loading rate of 10 kg COD m^{-3} d^{-1}.

1. Introduction

Fuel cells are power sources that use catalytic oxidation reactions without resorting to thermal processes, thus achieving direct conversion of chemical energy (of a generic fuel) into electrical energy. In particular, Microbial Fuel Cells (MFCs) directly convert the chemical energy contained into an organic bio-convertible substrate into electrical energy, through the mediation of exoelectrogenic bacteria that act as catalysers of the half-reaction of substrate oxidation [1].

When wastewater is used as anode fuel, MFCs perform wastewater treatment while recovering energy, thus leading to the possibility of energy-producing wastewater treatment plants [2]. Low power density and restricted output voltage of MFCs currently limit their industrial application [3]. Many approaches have been explored to enhance the performances of exoelectrogenic bacteria, to accelerate their growth and to decrease the start-up time needed. These include selection of the inocula [4], electrode

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potential poisoning [5] and variations in load resistance [6]. Another alternative, not yet fully exploited, is to enhance MFCs power output by controlling the electrical load to always produce the maximum power output [7]. The maximum power, as in any other electrical power source, is drawn when the external resistance (R_{ext}) equals the internal resistance (R_{int}) of the system [8]. More than 50% of the power can be lost if the electrical load is not matched with the internal resistance [7]. Hence external resistance should be (at least) periodically adjusted in order to follow the Maximum Power Point (MPP) [9].

Several Maximum Power Point Tracking (MPPT) methods have been proposed in the literature. One class of MPPT methods uses a mathematical model of the system to compute its impedance (internal resistance in case of direct current) [7,9]. The main problem of such an approach is its complexity and the amount of parameters to calibrate. Another class of methods is represented by non-model based, real-time optimization methods, mainly studied for fast dynamic systems. A real-time optimization method can be used to adjust the value of MFC external resistance, in order to maximize the electrical power delivered at each moment [7]. The R_{ext} control could represent an important requirement in case of wastewater treatment application of MFCs, since the influent quality and the plant operational parameters could vary over daily and/or seasonal basis [10,11].

The first study about MPPT control application to MFCs was carried out by Woodward et al. (2010). They applied and compared different MPPT methods for tracking optimal R_{ext} in two replicate MFCs fed with acetate [7]. In particular, they tested a Perturbation and Observation method (*P*/*O*) and a Gradient method (*G*) for the optimization of individually working cells, plus a Multiunit Optimization method (MU), useful in case of stacked MFCs (fully described in Ref. [12]). The authors concluded that *G* method, even if (in theory) it converged faster than *P*/*O*, was difficult to set up and did not ensure stable performances. On the other hand, *P*/*O* method was easy to tune and showed robust operation. Pinto et al. (2011) [10] tested again the *P*/*O* method on MFCs fed with acetate, and studied the control system performance during long-term operation. They found out that the load-controlled MFC exhibited higher current density and Coulombic efficiency compared to uncontrolled cells, and shorter start-up time (less than 10 days). Moreover, MPPT control application limited MFC methane production during the start-up phase [10,13]. Degrenne et al. (2012) tested a different algorithm to control the external resistance of MFCs [14]. The new algorithm was able to impose a cell voltage equal to one-third of the Open Circuit Voltage (value approximately corresponding to the MPP) but did not show significant advantages with respect to the *P*/*O* method. Boghani and coworkers (2013) [15] tested another MPPT system based on a parsimonious gradient based method (fully described in Ref. [11]). They coupled it with an additional start-up routine, able to poise the anode potential until the current sourced from the MFC did not exceed a certain threshold (method called PP-MPPT). This approach was able to reduce MFC start-up time of about 3 weeks, improving exoelectrogenic bacteria selection and activity (increasing the Coulombic efficiency), avoiding power overshoot during the biofilm enrichment period [16,17] and reducing methanogenesis in the anode compartment. However, the MPPT system alone exhibited similar benefits to the more complex PP-MPPT [15]. It appeared to be better (and easier) to follow directly the MFC internal resistance behavior, and hence MPP variations, with respect to poise the anode potential to values that could be unsustainable for early-stage biofilms.

Automatic resistance control was proven to influence also the exoelectrogenic microbial community composition [6,9,11,13,18] and abundance. Premier et al. (2011) observed that the biomass present in a load-controlled MFC was less than half that in a replicate cell equipped with a static resistance [11]. On the other hand, the power output did not seem to be affected by any control system until the applied resistance remained near the optimal value [5,15,18].

All these results demonstrated the advantages of using a MPPT system to control the current sourced from MFCs. In particular, the *P*/*O* method seemed to be the best compromise between precision, robustness and easy implementation [7]. The automatic resistance control certainly represents a step towards the industrialization of the MFC technology, but still today the specialized literature is lacking of experimental works on scaled-up reactors and/or real wastewater utilization. This paper aims to start filling the gap, offering a comparison between two replicate MFCs, one with the MPPT control applied and one acting as reference cell, equipped with a fixed resistance. Continuously fed swine wastewater was used as anode substrate, in order to evaluate the system under real and dynamic conditions, from an industrial-oriented point of view. Very few studies in the literature demonstrated the feasibility of animal wastewater treatment and bioenergy production using MFCs [19,20].

A complete assessment was carried out in terms of power produced, current intensity, internal resistance, energy losses distribution, organic matter removal and Coulombic efficiency. The effects of MPPT control application were evaluated at short-term and long-term conditions.

2. Materials & methods

2.1. Experimental setup

Two replicate MFCs were operated under different electrical load conditions to evaluate the effects of a MPPT system on their bioelectrochemical performances. In particular, one MFC was subjected to the MPPT algorithm (MPPT-MFC) for automatically controlling the electrical load applied, while the other one was equipped with a fixed external resistance of 30 Ω (Ref-MFC). This resistance value was chosen in order to be near to the static internal resistance of the MFC, based on previous experience gained on similar working cells [21].

The MFCs were constructed using a previously described design [22], and consisted (each one) of an anode and a cathode placed on the opposite sides of a single methacrylate rectangular chamber. The anode and cathode chambers were filled with granular graphite (model 00514, diameter 1.5–5 mm, EnViro-cell, Germany), which decreased the volumes to 370 ± 10 mL net anodic compartment (NAC) and 410 ± 10 mL net cathodic compartment (NCC) respectively. The electrodes were previously washed in 1 M HCl and 1 M NaOH to remove possible metal and organic contamination. Two thinner graphite rods electrodes (250 × 4 mm, Sofacel, Spain) were introduced in each chamber to allow an external electrical connection to the system. An Anion Exchange Membrane (AMI-7001, Membranes International Inc., USA) was placed between the anode and cathode frames. The AEM membrane was chosen because of its lower internal resistance and diffusivity to oxygen, that should allow to achieve higher power densities and Coulombic efficiencies [23].

Swine wastewater from the Food and Agricultural Research Institute (IRTA) of Monells (Girona, Spain) was used as anode fuel. The liquor was stored in a refrigerated tank to promote solids settling and to preserve the organic matter content. The swine wastewater was continuously fed to the anode at a flow-rate of 1.5 L d^{-1}. The cathode was fed, at the same flow-rate, with an oxygen-saturated mineral medium with the following characteristics: 122 mg L^{-1} $NaHCO_3$, 7.6 mg L^{-1} NH_4Cl, 300 mg L^{-1}