EVALUATION OF THE ELECTRICAL PERFORMANCE OF A SOIL-TYPE MICROBIAL FUEL CELL TREATED WITH A SUBSTRATE AT DIFFERENT ELECTRODE SPACINGS

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Abstract

The effect of electrode spacing on the performance of a microbial fuel cell (MFC) under batch treatment with a substrate was investigated with three single-chamber MFCs built with biologically active soil. The electrodes consisted of a stainless-steel mesh with layers of activated carbon catalyst. The MFCs were fed with artificial urine after reaching a stationary phase. After the initial treatment, the cell with the smallest electrode gap produced the maximum peak power under polarization. At 2 cm, 5 cm and 8 cm electrode spacing, the maximum power was 726.2 μW, 547 μW and 520.3, respectively; while the average power of the MFCs from the first point of treatment with substrate to the last point was 297 ± 259.2, 505.43± 42.5 and 433.81± 64, respectively. A significant decrease in internal resistance of the MFCs was observed during batch treatment. The impedance analysis of the MFCs showed that the reduction in internal resistance was largely due to a significant decrease in ohmic resistance compared to the charge transfer resistance.

Keywords: Microbial fuel cell, soil, electrode spacing, substrate

1 INTRODUCTION

Apart from the popular renewable energy resources such as wind, geothermal, and hydropower and modern bio-energy, microbial fuel cells (MFCs) are recently becoming prominent in research domain as a possible component of these alternative sources of energy [1,2]. The general idea behind MFC technology is the simultaneous treatment of wastewater and power generation. However, the electricity generated in this process till date is still very low due to the losses involved. Recent studies have shown that single chamber MFCs that use soil or solid anolyte [3], which are not necessarily used for wastewater treatment, have very high potentials for practically usable electricity generation [4]. This is related to the additional advantages that soil or sediment MFCs (SMFCs) offer compared to conventional MFCs.

Besides the abundance of complex sugars and other nutrients that accumulated over millions of years through the decomposition of plant and animal material [5]**,** the soil is rich in a mixed population of microorganisms such as bacteria, actinomycetes, fungi, algae and protozoa [6], and therefore SMFCs generate much higher power densities than those with pure cultures [7]**.** The use of mixed cultures offers a high microbial diversity, which allows different types of substrates to be used in MFCs under non-sterile conditions [8]. The enhanced substrates utilization in conjunction with S-MFCs can be associated with the symbiotic relationship that exists between the mixed microbial population, so that complex organic materials present in the medium, such as lignin and cellulose, which normally cannot be degraded or digested by the bacteria, are degraded by the fungi, releasing the simple nutrients inside to allow the bacteria to use them as substrate. Again, the soil or sediment contains aerobic, anaerobic and facultative microbes such as *Shewanella oneidensis* with remarkably different respiratory capacities [9, 10] and electroactivity [11]. This makes soil an excellent source of electroactive bacteria for MFCs that use synthetic or natural wastewater as substrate. The aerobic bacteria in the soil are beneficial in MFCs because they consume the oxygen around the anode and thus protect the metabolism of the anaerobes.

The abundant complex sugars and other nutrients in the soil form the natural starting substrates for the growth and maintenance of the activities of the electroactive bacteria (EAB) in a bio-electrochemical system. Therefore, when the soil is saturated with water, it contains the EAB and the substrate needed to maintain the metabolic activities of the microbes until the stationary phase (or the point of maximum achievable performance) is reached [12]. As beautiful as these MFC types sound, they suffer a sharp drop in energy production due to increased internal resistance once they are depleted of their natural substrates [13]. For long-term application of S-MFCs, it is therefore essential to replenish the substrates after exhaustion.

In a previous study, it was reported that the occasional injection of substrates in the form of human urine into SMFCs (with an anode-cathode distance of 4 cm) resulted in improved and fairly stable performance under various external loads [14]. However, it was observed that the initial maximum performance of the MFC could not be maintained over the entire study period due to oxygen diffusion into the anode region. This represents a limitation for the long-term operation of the S-MFC with wastewater as substrate. It is not common or conventional to treat S-MFCs with natural or synthetic wastewater, due to their configurations-a typical SMFC uses a single chamber configuration with the cathode placed at some distance above the anode to create a natural potential and a proton exchange membrane. Injecting a substrate into such a system therefore intermittently interrupts its continuous operation. However, in order to continue to draw maximum power from such a system, a batch treatment with a substrate is necessary. For this purpose, an anode-cathode interval must be found at which the effect of oxygen diffusion into the anode region is minimal and power output is optimal.

In general, the power output of MFCs is inversely proportional to the anode-cathode interval [15, 16]. This may not apply to S-MFCs, especially if they are treated with a substrate. A too small anode-cathode interval may result in high oxygen availability at the anode. This would promote the growth of aerobes around the anode, and competition for available nutrients would reduce the activity of the EABs resulting in a down-trend performance. On the other hand, a too large anode-cathode distance can lead to a slow mass transport through the mud, which limits the availability of substrate at the anode. Too large anode-cathode distance would also limit the movement of protons (mainly H+) and other cations such as K+, Na+ and Mg+ towards the cathode [17]. In any case, the biocatalytic activity and thus the power density of the S-MFC is negatively affected. There is therefore the need to optimize the electrodes spacing of SMFC for efficient substrate utilization.

To the best of the authors' knowledge, no study to date has reported the best anode-cathode distance (for a given cell volume) for long-term extraction of maximum power from S-MFC under batch treatment with a substrate. Therefore, the present study was designed to fill this gap.

2. MATERIALS AND METHODS

2.1Construction of MFCs and Electrodes

Each MFC consisted of a cylindrical glass vessel with an opening at the bottom next to the anode position for sampling. The cell had a screw cap with two 2 mm holes for connecting current collectors and a 6 mm hole for proper cathode ventilation. All vessels were designed with a diameter of 78 mm, but with different heights (60, 90 and 120 mm) to accommodate the electrode spacings. The electrodes were developed by integrating a stainless-steel (SS) wire mesh, an activated carbon catalyst layer and a binder into one unit. The stainless steel (type 1.4301, Germany) had a mesh size of 0.315 mm and a wire thickness of 0.2 mm with 50 meshes per square inch. The activated carbon (Carbon Black - Vulcan XC 72, Keego Tech., Texas) was applied to the SS with a 2-component epoxy adhesive (UHU plus ENDFEST, Germany) to form composite electrodes. Both the anode and cathode had a diameter of 6.5 cm.

2.2 MFCs Set-up and Operation

Compost and top soil collected from the Botanical garden of the university of Bayreuth, Germany, were sieved with a 2 mm stainless-steel sieve. Mud was prepared from 1:1 of the two soil types as previously described [13]. Each MFC (Figure 1) was set up by placing about 1 cm of mud at the bottom of the MFC vessels before installing the anode. Additional mud was deposited on top of the anode according to the electrode spacing design and then the cathode was installed such that there was a space of about 40 mm between the cathode and the cap in order to allow for proper aeration of the cathode.

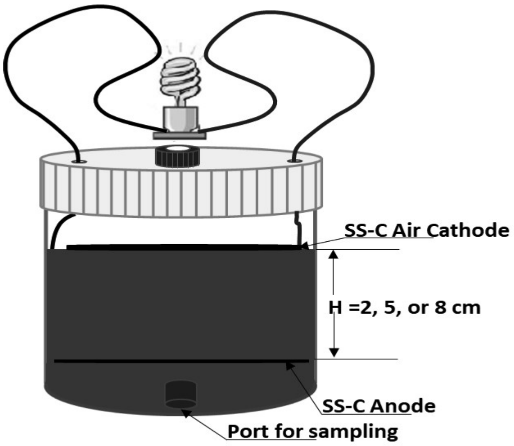

Figure 1. Schematic of the Set-up
For electrode spacings of 2, 5 and 8 cm the MFCs were designated as MFC_2h, MFC_5h and MFC_8h, respectively.

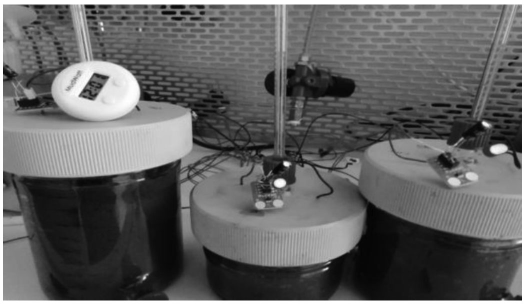

Figure 2. Pictures of MFCs Powering devices. *On day 30, the MFCs were connected via the Mudwatts Hackers board (Keego Technology) to power LEDs and digital clocks.*

The MFCs were connected to a data logger (ADC-24, Pico Technology) to measure the open circuit potential every one hour. The growth of the electroactive biofilm on the anode was monitored with the aid of the graph from the data logger. When a stationary growth phase was reached, suggesting the exhaustion of the available substrate, synthetic urine medium prepared according to the method described by [18] was fed into the cells. In accordance with a previous study [14], the addition of substrate was repeated every sixth day and each MFC was treated with 10ul/g of mud. The performance of the MFCs was assessed with Liner sweep voltammetry and electrochemical Impedance Spectroscopy techniques using a potentiostat (Bio-logic SAS VMP3). The total internal resistance was obtained from the current and voltage parameters of the maximum power point using equation 1

$$R = \frac{V}{I} \tag{1}$$

where R is resistance in Ohms, V and I are voltage and current at MPP respectively

3 RESULTS AND DISCUSSIONS

Figures 3 to 6 show the performance of the MFCs throughout the study period

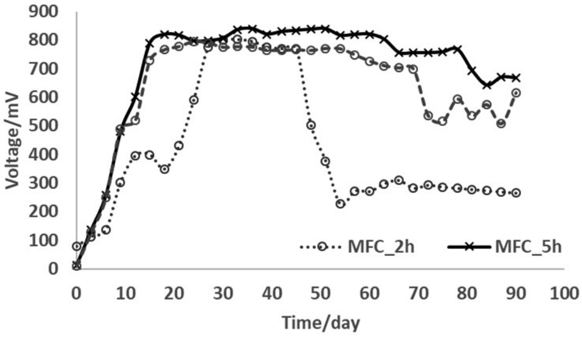

Figure 3. Change in Open Circuit Voltage of the MFCs

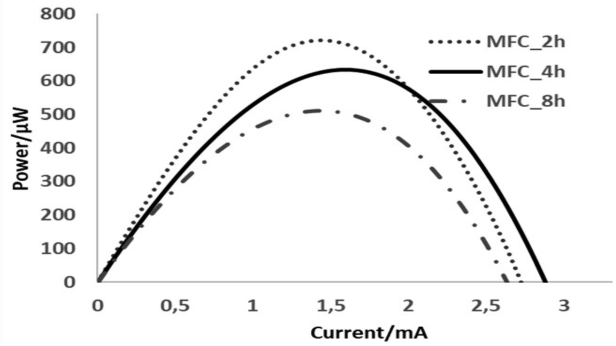

Figure 4. Power Curves of the MFCs. *The power curves were obtained from linear sweep voltammetry performed on day 30. The MFCs were polarized at open circuit potentials in a two-electrode system with anode as the working electrode and cathode as the counter and reference electrode.*

Between day 1 and day 30, the open-circuit voltages and power of MFC_5h and MFC_8h were higher than those of MFC_2h, contrary to expectations, since the electrode spacing and internal resistances of MFC_2h were lower at these points. The electrical power of MFCs have been reported to be inversely proportional to their anode-cathode distance [19]. However, the results of the present study clearly show that too small an electrode spacing in SMFCs does not follow the normal trend. Since an SMFC uses an air cathode in the same chamber with the anode, the influence of oxygen diffusion through the soil or sediment would be higher at smaller electrode spacings. This has a negative impact on the bio-electrochemical activities of the electroactive microbes associated with the anode. Similarly, it is also evident that MFC_2h with 2 cm electrode spacing was easily depleted of its natural substrate and moisture, probably due to evaporation. This is not unexpected since the mass of the mud and consequently the microbial density and volume of the substrate was lower in MFC_2h compared to MFC_5h and MFC_8h. The maximum power was obtained with 2 cm electrode spacing due to readily availability of substrate and lower internal resistance, but this could not be sustained on a long-term operation as shown in the figures due to the impact of oxygen diffusion. Towards the 90th day, it was observed that the internal resistance of the MFC_5h increased (Figure 6) leading to a gradual decrease in power, while a gradual improvement in the performance of MFC_8h was observed; this implies that the MFC_8h could have a better performance over an extended time.

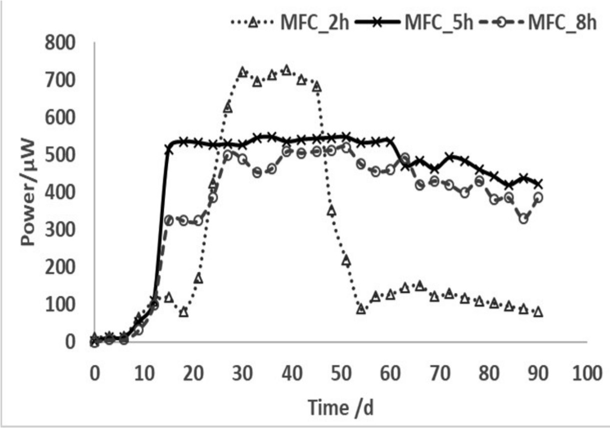

Figure 5. Change in Maximum power with time. *The MFCs were polarized every 3 days between open circuit potentials and zero in other to obtain the MPP*

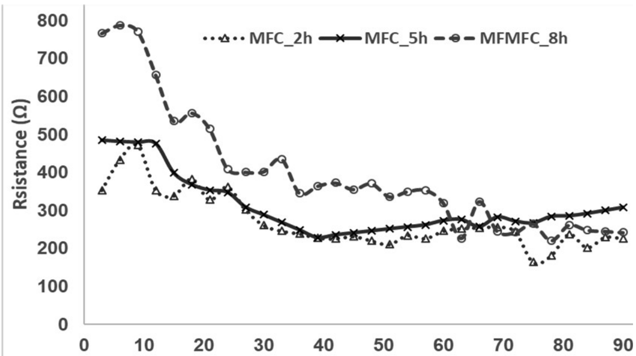

Figure 6: Variation of total internal resistance with time

The ohmic resistance of MFCs is theoretically proportional to the electrode spacing [20]. This also applies to the MFCs in this study (Figure 7). The total internal resistance shown in Figure 6 showed the same proportionality until day 60. On day 63, the resistance of MFC_8h with the highest electrode spacing (8 cm) was lowest and its performance coincided with that of MFC_2h. After day 65, an upward trend in the resistance of MFC_5h was observed. The increase in internal resistance observed with MFC_5h was largely due to the increase in charge transfer resistance (Table 1). This could be due to electrode fouling due to substrate concentration at the cathode or to an increase in the thickness of the anodic biofilm.

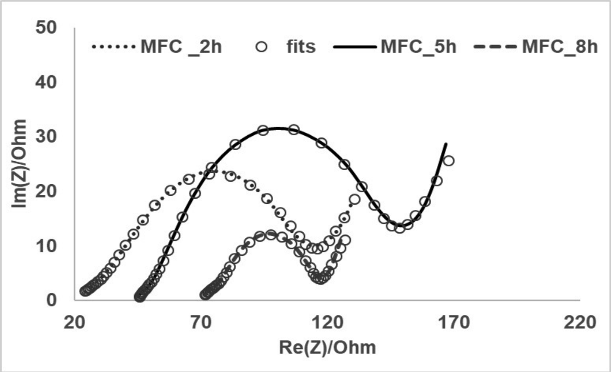

Figure 7. Nyquist impedance of the MFCs on day 90. *EIS was performed on a full cell basis using two electrode system, with anode as the working electrode and cathode as the reference and counter electrode*

Table 1. Parameters of the Nyquist plots

	R1	R2 + R3	C2/F
MFC_2h	24,16	95,02	3,29E-04
MFC_5h	46,27	100,4	4,59E-04
MFC_8h	71,72	47,32	4,27E-06

The Nyquist impedance parameters (Table 1) were obtained by simulating the electrochemical impedance spectroscopy to the equivalent circuit R1+C2/R2+Q3/(R3+W3), Although the ohmic resistance of MFC_8h was higher compared to the other two MFCS, it had the lowest charge transfer resistance and the lowest double layer capacitance. This shows that apart from cathode fouling, an increase in the thickness of the anodic biofilm led to the observed upward trend in the internal resistances of MFC_2h and MFC_5h. The direct cause of this observation is obviously an accumulation of non-electroactive microbial species at the anode of the MFCs as a result of oxygen diffusion.

4 CONCLUSIONS

In this study the performance of an SMFC was evaluated under different electrode spacings. The study showed that a cathode-anode distance of 5 cm ensures substrate availability at the electrodes and minimal oxygen diffusion to the anode to maintain bacterial metabolism, resulting in stable performance of the soil MFC over the period of the study. Although the maximum performance was achieved at a distance of 2 cm due to easy availability of the substrate and the lower internal resistance, the effect of oxygen diffusion was also highest, resulting in a rapid drop in its performance. The impedance analysis of the MFCs on day 90 showed that at an electrode spacing of 8 cm the charge transfer and double layer capacitance were lowest, the point at which a gradual increase in its power was observed. This clearly showed that the influence of oxygen diffusion is more pronounced at lower electrode spacings. It is recommended that the study duration be extended beyond 90 days to better understand the performance of the MFCs in this study.

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