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Ceramic MFCs with internal cathode producing sufficient power for practical applications

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ABSTRACT

This communication reports on the potential of using MFCs for powering real world applications, whereby three interconnected MFCs directly energise an external DC motor, and a single MFC recharges a mobile phone, via energy harvesting. The work is aiming to evaluate MFC performance based on low-cost, catalyst-free conditions, with an internal cathode to operate practical applications. It presents the case for simple and easy-to-operate ceramic-based designs as a viable approach to larger-scale implementation in real-world conditions such as wastewater treatment plants. MFCs hold great promise for sustainable wastewater treatment since they are the only technology that directly generates electricity from the break-down of waste.

Introduction

Providing adequate sanitation and clean water to a global population is today's economic challenge. Microbial fuel cells (MFCs) have the potential for direct biological conversion of wastewater organic materials directly into electricity [1]. Significant improvements in power performance have been achieved in the last 2 decades, so the successful, commercial real-life MFC demonstration is closer than ever before. Recent advances in various fundamental areas can lead to practical applications [2] and subsequently to commercial use. Substantial progress has been made towards enabling the implementation of this technology by replacing expensive components such as platinum electrodes with carbon, membranes with ceramics [3,4] simplifying operational conditions [5] and modifying reactor designs [6]. In a recent review the design optimisation, improved harvesting and cost reduction have been identified as the main areas that require improvement towards the generation of practically usable power [7]. A better understanding of the impact of reactor components on the performance of the system is an important step towards commercialisation of Bioelectrochemical Systems (BES) [8,9]. The major hurdles are being recognised in design and engineering rather than biology [10]. Understanding these phenomena can allow us to identify ways of optimising reactor

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design, process conditions, and optimal outputs. The efforts to implement the MFC technology into wastewater treatment plants have thus far been limited by relatively low power densities, however, in a recent study a single MFC was powering a pump intermittently in the aerated lagoon treatment system improving organics removal [11]. At the same time, scale-up attempts have investigated various approaches such as a plate [12], cassette [10] or tubular systems [13–15]. In general, the multiplication and miniaturisation offers an alternative way of scaling up [16] that could be used to power mobile robots [17], due to the increased power density of miniaturised MFC units [18]. In this respect, a stack of tubular MFCs provides a method of obtaining high surface areas in standard (inner anode, outside cathode) configurations and it has been shown to power a commercial mobile phone handset [19]. The objective of this work is to present the inverted configuration where the anode is placed outside and the cathode inside the tube to emphasise the practicality of the internal cathode design in the MFC. In this way, the proposed simple and cost effective design can be used as a functional unit by directly immersing it in wastewater tanks. With a reversed electrode set up, this work is leading further into simultaneous water recovery in the form of catholyte [20] that could be collected from the internal cathode chamber [21], which is the reason why the energy-rich organic waste streams can be used as a high value fuel, increasing energy recovery. This work aims to present the essential component of catholyte accumulation (known in chemical fuel cells as "flooding") inside the cathode chamber improving – instead of hindering – the performance. Furthermore, it is also aimed to demonstrate the practical use of these MFCs, by (i) driving a motorised model windmill directly using 3 MFCs connected together and (ii) charging a mobile phone via energy harvesting electronics using a single MFC.

Experimental

MFCs were assembled using sealed at one end, 10 cm long, 3 mm wall thickness terracotta caves (Orwell Aquatics, UK) serving both as the MFC casing and a separator between the anode and the cathode. Anode electrodes were 2430 cm^2; 20 gsm carbon fibre veil (PRF Composites, UK) wrapped around the ceramic cave and pressed against the wall with nickel chromium wire (0.45 mm diameter). Cathode electrodes were made of activated carbon and PTFE paste applied on the same carbon fibre veil substratum (90 cm^2; 20 gsm) as previously described [21] and placed inside the cylinder so the activated carbon was facing the ceramic wall. A stainless steel crocodile clip and Ni-Chr wire was used for connecting the cathodes. The terracotta MFCs were placed inside plastic containers, inoculated with 200 mL of activated sludge provided by Wessex Water Scientific Laboratory (Cam Valley, Saltford, UK) and operated in batch conditions to assess the performance and catholyte accumulation. The anolyte was periodically supplemented with a mixture of activated sludge and 20 mM sodium acetate at pH 6.7–7.9. A total of three MFCs (units labelled as T1–T3) were tested under an external resistor load of 53 Ω and a further 3 MFCs were tested under open circuit conditions (units labelled as T4–T6). All tests were performed under room temperature, 22 °C, without pH control or any platinum catalyst.

A model windmill equipped with a DC electric motor (RF-300CA-11440 DC/2.0V 11303, HSC Motors) was employed as a practical demonstrator of the usable power from the three parallel connected MFCs. A 300F 2.7 V max. super-capacitor (XW3550/2R7307/R, Cooper Bussmann) was also used to store excess energy in addition to powering the windmill.

Furthermore, a mobile phone Samsung GT-E2121B was connected via a Texas Instruments energy harvester (TI BQ25504EVM-674, Farnell, UK). The output voltage from the single ceramic MFC was insufficient to meet the voltage requirements of the phone battery and charge it directly, hence the energy harvester was used. Data logging was performed via a multichannel DAQ Agilent 34972A (Farnell, UK). Current and power output levels were calculated as previously described [18].

Results and discussion

Performance

Tubular MFCs were tested in closed circuit conditions, under 53 Ω external resistor (T1, T2, T3) and in open circuit conditions (T4, T5, T6). A stable power output was recorded over a period of 7 days with an average of 805 μW, 458 μW and 880 μW, for T1, T2 and T3 respectively, whilst the open circuit MFCs produced open circuit voltages of T4 649 mV, T5 638 mV and T6 656 mV. To demonstrate the useful power levels of the tested units, T1, T2 and T3 had their external resistors removed and connected in parallel directly to power the windmill motor. The substrate was replenished by fresh sludge+20 mM sodium acetate at pH 7.9 and conductivity of 17.7 mS/cm. Fig. 1A illustrates the voltage and current behaviour of the MFCs energising the windmill DC motor. As can be seen, the voltage output was steadily increasing over a period of 3 days, from 245 mV to 265 mV, after which period a current probe was connected to measure the current directly, which was shown to be approximately 9.6 mA throughout. The test also included connecting a 300F super-capacitor to the circuit, whist the motor was still running, showing excess amounts of electricity that could be stored in a system during continuous operation. This shows that the additional energy stored in the capacitor would make the system more efficient. At the end of the 6th day, the motor stopped when the voltage level dropped below 200 mV. It was observed that during this practical demonstration catholyte was produced and accumulated in the internal cathode chamber. On average, as shown in Fig. 1B, MFCs powering an external circuit generated 44 mL of catholyte whilst the open circuit MFCs produced only 9.6 mL, which is a significantly less volume. This suggests that some passive diffusion through the terracotta material was occurring primarily for the open-circuit MFCs, but when under load, anolyte was transported via electro-osmostic drag [13]. Catholyte properties include a significantly higher pH level and approximately a two-fold increase in conductivity compared with the catholyte formed from the open circuit MFCs. This might be one reason why MFC operation was improved [22]. Similar caustic catholyte formation in MFCs

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