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Microbial fuel cell stack power to lithium battery stack: Pilot concept for scale up

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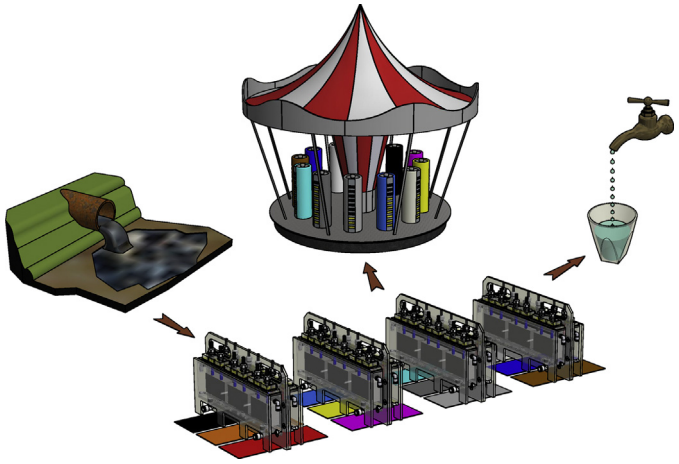
HIGHLIGHTS

- Subdivided shared 12 unit MFC-stack improved power 8.5 times.
- MFC-stack to lithium battery-stack charging process was balanced.
- All 12 MFC unit voltages were monitored while charging lithium batteries.
- Voltage reversals were absent permuting lithium batteries.
- Lithium batteries permutations enabled faster and simultaneous charging.

GRAPHICAL ABSTRACT



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ABSTRACT

A stack to stack microbial fuel cell power to batteries storage was investigated on the pilot scale with the aim to scale up in future. A 12 unit MFC-stack, equipped with maximum power point tracking (MPPT) and lithium polymer batteries (3.7 V), was set up. The MFC-stack architecture was simplified by sharing partially electrolytes. The serial 12 unit MFC-stack was first used as a linear assembly of all MFC units and then subdivided into three MFC-sub-stacks which enhanced power extraction by 8.5 times. To balance the stack power generation, the external circuits were alternated into zigzag, braid and random figurations as well in rational directed configurations. Finally, batteries permutation along with MPPT enabled faster and balanced lithium battery stack charging. Balanced conditions resulted in time shift oscillations, the absence of unwanted power pooling and voltage reversals. All in all, the work showed how to generate and store power from an 12 L microbial fuel cell stack with partly common electrolytes.

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1. Introduction

Microbial fuel cells (MFCs) oxidise biomass and organic matter into bioelectricity through microbial activity [1]. Many substrate-microbe combinations, that readily generate electric power are known [2]. However, MFCs release of biological powers and their best achievable production potentials are hardly above 0.5 V [3]. To obtain useful voltages and currents, the serial stacking of multiple MFCs has been proposed [4]. Allometric scaling from data in the literature suggests that MFC-stacks with small MFC units are easier to extract power from [5]. Experiments with 5 and 10 unit MFC-stacks showed that electricity generation directly correlated with available electrode surface [6]. Finally the number of needed MFC units for a well-performing MFC-stack is best calculated from polarisation data based on the specific MFC units in the stack. This MFC-stack characterisation should equally include power generation trials, in order to understand whether power maxima (P_{max}) can be reached against the defined resistance load at P_{max}. Another important prerequisite is to find electronic components for power management and storage (e.g. battery, grid).

With ~10 or more MFC units various MFC-stack assemblies are possible [7]. To date, the preferred MFC-stack organisation is the serial alignment of multiple MFC units because it has repeatedly been found to be slightly more performant than parallel assemblies. In parallel stacks energy losses were detected under closed circuit conditions [8]. Likewise mixed parallel-serial connections were investigated in order simplify larger stacks [9]. Although serial stacks perform better "in theory", they require strict control in particular due to internal resistances [10] in order to maintain high performance [11]. In specific applications, stacked serial MFCs are usually preferred as they generate higher power than parallel setups, i.e. CO_2 reduction to formic acid [12] and wastewater treatment [13]. Moreover, it was usually preferred to work with well separated MFC units to avoid power loss by substrate cross conduction [14], which is also described as ionic cross conduction [15]. Well-defined MFC-stacks with separated electrodes were shown to be powerful and enabled even to charge and run smart phones [16]. But, the processing of MFC-stacks with well-separated units reduces performance and simplified constructions are needed for MFC-stacks to become economic [17]. For example, liquid pumping for each MFC unit leads to mechanical energy loss and should be avoided [18]. Less energy consuming pumping is possible with MFC-stacks with shared electrolytes [13]. Such MFC-stacks can be established with tubes having multiple sections with single chamber MFCs [14]. A second option is to plug multiple tubes, such as, reversed single chamber MFCs, into a shared anolyte and connect them as a stack [19]. The use of baffled MFCs enables also the use of common anolytes on the 90 L scale [18]. Finally, electrolyte sharing can be implemented by multiplying dual chambered MFCs into shared systems that are interconnected as stacks [20].

The reasons and resolutions for the low performance of MFC-stacks with shared electrolytes are being increasingly researched [21]. Asymmetric performance was observed in particular when fully shared anolyte MFC-stacks were used [19]. Similarly, MFC-stacks with continuous anolyte flux that passed from one half cell to the next via external tubes also showed similar effects. One reason was that the electrolytes became depleted in substrates in the first units which leaded to less performant units at the end of the stack (i.e. fuel depletion). But imbalances also occurred in batch processing due to different internal and external resistances. Therefore shared electrolyte MFC-stacks need to be further examined in order to balance and improve power generation to the level that they can become competitive with non-shared MFC-stacks.

Beside stack's balance, stress tolerance of electrogenic microorganisms in MFC-stacks is important to consider. Microbes do not easily sustain high voltages and elevated stack currents appear particularly problematic for weak biofilms in an MFC-stack [22]. This is because electrogenic microorganisms are forced to generate a current beyond their metabolic capacity (i.e. stack currents are identical in all MFC units). Above a certain critical current, biofilms were shown to become dysfunctional or even collapsed. But by controlling the current, the biofilm persisted longer [23]. Discharging currents were found to be beneficial for the electricity generation by biofilms, whereas this capacity was lost with elevated currents [24]. Little is known concerning the critical level of these currents and how the induced stress in anodic biofilms can be conveniently monitored.

Electric and magnetic stresses were found as a means to stimulate biofilm growth [25]. In contrast, high stack currents turned biofilms acidic, which reduced the biofilm survival and electricity generation [26]. Briefly, the pH drop resulted from electron transfer to the anode, producing stoechiometric quantities of protons. These co-produced protons are expected to be transferred through the outer cell membrane, before migrating through the cation exchange membrane into the cathode. However, this proton transfer [27] was slow in comparison to electron conduction through the external circuits [28]. In addition, protons were withheld by anodic buffers and consequently substituted by sodium, potassium and other cations. Those cations migrated into the cathode instead of the protons [29], which increased strongly the catholytic pH [30]. Consequently, protons accumulated in anodic biofilms and reduced the biofilm's capacity to generate currents, and weaken the biofilms [31]. Such effects were also visualized to understand proton distribution in anodic biofilms [32].

To summarize, shared electrolyte MFC-stacks are simplified MFC constructions and therefore are considered for low-cost electricity generation in waste water treatment plants [33]. A better understanding of MFC-stacks functioning and the impacts of biofilm is needed for efficient scale up [34].

In this work, a 12 L MFC-stack made of 12 units was constructed with shared electrolyte cavities in order to simplify MFC architecture. Electric power generation was compared with a serial MFC-stack arrangement and a newly elaborated sub-divided MFC-stack organisation. Up to three lithium-polymer-batteries were charged simultaneously to examine stack to stack power storage. Maximum power point tracking (MPPT) was implemented to optimize power extraction. Several methods were developed to ensure well-balanced power generation with partly shared electrolyte MFC-sub-stacks. This included: circuit alternations, power tracking resets, and battery permutation. In addition, more insight into the origin for voltage reversals and time shift oscillations were gained.

2. Material and methods

2.1. Microbial fuel cell construction

A 12 L 12 unit MFC was constructed consisting of a stack of four triple MFC modules (*Modules 1–4*) (Fig. 1, left). A single MFC module consisted of a triple stack MFC reactor, which contained three anodes in a common anode cavity of 1.5 L and three cathodes in a common 1.5 L cathodic cavity. The MFCs were built from polycarbonate in-house (Angst + Pfister, Switzerland) [20]. The 24 electrodes (130 × 30 × 70 mm) were made from reticulated vitreous carbon (RVC) 100 PPI (ERG Aerospace Corporation, USA). The anodes and cathodes were separated by Nafion® N117 proton exchange membranes (PEM) (Ion Power Inc., Germany) with a corresponding surface to the electrodes exposed surface area.

2.2. Power tracking storage unit

Maximum power point tracking (MPPT) [35] was combined with power storage electronics to charge a polymer lithium battery of 3.7 V (Fig. 1, right). Three of such identical Power Tacking Storage Units (PTSUs) were built on electronic boards from commercially available components. The PTSU enabled the power tracking, to charge and discharge a lithium polymer battery (1S) of 3.7 V/500 mAh (E-flite).