Optimisation of Scale-Up of Microbial Fuel Cell for Sustainable Wastewater Treatment with Positive Net Energy Generation

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Abstract:

From eight to fifteen litres of liquid by-products are generated for every litre of grain whisky produced. 'Spent Wash' is the main liquid stream. If discharged untreated into the environment it might contribute to pollution such as eutrophication.

Microbial Fuel Cells (MFCs) are a natural bio-technology solution to the issue working either independently or in conjunction with established wastewater treatment technologies. Utilising metabolic reactions of electrochemically active microorganisms, MFCs provide a dual benefit: wastewater treatment and direct electricity generation. For industrial applications, scalability through plurality can be the solution. Multiple units of relatively small scale can be connected to achieve the necessary capacity.

Initially a single chamber open air cathode MFC of 170ml volume treating spent wash subsequent to anaerobic digestion treatment demonstrated an average voltage of 0.4V in open circuit and a COD reduction efficiency of 67%. Scaling up, a 100lt unit operating in directly diluted spent wash at 0.55g COD/l.d demonstrated 90% COD removal, maximum voltage 0.65V over a short circuit current of 163mA. Ongoing experiments using this configuration and previously anaerobically treated spent wash demonstrate encouraging results, bringing practical industrial scale Microbial Fuel Cell treatment closer.

Nomenclature

MFC	microbial fuel cell
MFC_1	1st electrode pair in MFC
MFC_2	2nd electrode pair in MFC
MFC_3	3rd electrode pair in MFC
MFC_4	4th electrode pair in MFC
HRT	hydraulic retention time
OCV	open circuit voltage
SC	short circuit voltage
P_{max}	maximum power generation
COD	chemical oxygen demand
COD_{in}	chemical oxygen demand of influent
COD_{out}	chemical oxygen demand of effluent
E_{COD}	chemical oxygen demand removal efficiency
E_{emf}	overall electromotive force

1. Introduction

The global energy crisis along with the unsustainable supply and use of fossil fuels are the main drivers for research of alternative, renewable and more sustainable sources of energy (Satyam at al., 2011). In the field of water demand, resources and sanitation in one hand, and treatment of wastewater on the other hand, technologies that require as low energy input as possible become increasingly attractive. Commercially available current technologies such as aerobic digestion in conjunction with established anaerobic methods pose issues such as high capital and operational costs largely due to intense energy consumption (Ghangrekar & Shinde, 2006).

Particularly in the food and drinks industry Microbial Fuel Cells have been identified as a natural solution to the issue of wastewater treatment. From eight to fifteen litres of liquid by-products are generated for every litre of grain whisky produced. 'Spent Wash' is the main liquid stream. If discharged untreated into the environment it can contribute to pollution such as eutrophication (Mohana et al., 2009). Utilising metabolic reactions of electrochemically active microorganisms Microbial Fuel Cells break down organic compounds in wastewater converting the chemical energy into electrical. Electrons are collected by the anode electrode in the anaerobic compartment and are transferred through external wiring to the cathode which in this particular case is exposed to ambient air (Logan et al., 2006, Zhou et al., 2014, Choi, 2015, Logan, 2008, Gálvez et al., 2009).

Initial experiments for the future development of a cascade industrial system started from laboratory scale and demonstrated promising results. Two single chamber open air cathode MFCs coupled to a single unit of overall 170ml active volume have been inoculated with anaerobic granular sludge and operated on liquid digestate exiting an anaerobic treatment plant. Typical preliminary results demonstrated an average COD removal efficiency of 67% (Dimou, 2012). Following on from the above, scalability was demonstrated with an overall 100lt single chamber open air cathode system based on typical materials commonly used for similar applications. Industrial scale applications in wastewater treatment are under research and development worldwide (Logan, 2010), therefore, the purpose of this experimental is to monitor and study the efficiency of both wastewater treatment of Spent Wash with the additional benefit of electricity generation through an MFC.

2. Methods and materials

2.1 MFC configuration

Initial studies were carried out in a 100lt microbial fuel cell which can be considered as a horizontal flow multi-electrode bioelectrochemical reactor (Fedorovich et al., 2009). Figure 1 demonstrates how the reactor embodies eight anode and cathode electrodes. Given that the anodic compartment is not distinct to the cathodic with a separator and the cathode is exposed to air, the MFC model can be considered single chamber open air cathode in terms of each anode-cathode pair. However, every two of the neighbouring pairs are coupled; the anodes are connected between themselves with wiring as are the cathodes. From these, the anode is connected to the cathode with an external circuit which consists of wiring, an on-on switch and an adjustable resistor.

In terms of liquid flow, the active volume is 57lt separated in four equal compartments. The influent (Figure 1) enters low down on the side towards the front, circulates from MFC_1 to MFC_2, MFC_3 and MFC_4 and finally exits from the top of the rear far side.

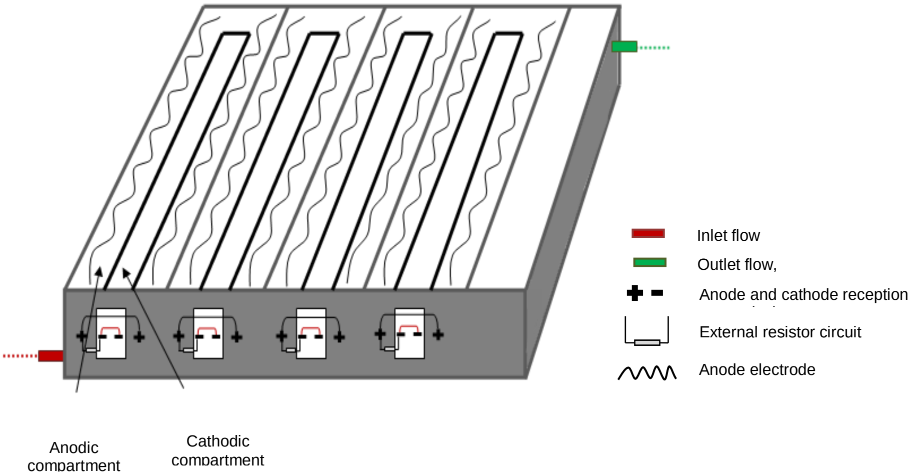

Figure 1: Schematic approach of 100lt MFC prototype reactor

2.2 Inoculum and operational parameters

The inoculum used was anaerobic granular sludge that had been adapted over three month period. The original inoculum was sourced from a local distillery from the Anaerobic Digestion unit operating on the premises. The MFC unit had previously operated under a different electrical regime while this current study focuses on a 90 days period operation under the system described above.

The single MFC operated in ambient temperatures during winter down to 3^{o}C. Average temperature of the effluent in the reactor during the initial experimental trial was approximately around 20^{o}C. Influent pH was kept at 6.7±0.4 and was pumped continuously in the reactor through a peristaltic pump. Hydraulic Retention Time (HRT) was kept at four days during the 90 days monitoring and the average influent COD value was 2213±773mg/l (organic load rate of 0.55gCOD/l.d).

2.3 Analysis, measurements and calculation

Electrical readings for each electrode pair include voltage and current. The method used was single-cycle method for which a 24h period was allowed for the voltage to reach a pseudo-steady state. Voltage and short circuit current were monitored with the use of a digital multimeter and external resistance was kept at minimum value (UNI-T, UT30B, UK). Maximum power output was calculated from Ohm's Law;

$$P_{max} = OCV \times SC \qquad \textbf{Equation 1}$$

COD was monitored as the main process observable according to standard methods (APHA, 1999). Samples were collected from the final exit point. The results of the above analysis were used for estimation of COD removal efficiency as shown below;

$$E_{COD} = \left(\frac{COD_{in} - COD_{out}}{COD_{in}} \right) \times 100\% \qquad \textbf{Equation 2}$$

where E_{COD} is the COD removal efficiency (%); COD_{in} is the COD concentrations of the influent (mg/l) and COD_{out} is the COD concentrations of the effluent (mg/l).

3. Results and discussion

3.1 Open circuit voltage (OCV)

As demonstrated in Figure 2 after change from the previous arrangement to the new electrical configuration, open circuit voltage needed approximately five days to reach a steady state of performance after which it maintained an average of 558±42mV, 614±33mV, 542±28mV and 589±62mV for the 1st, 2nd, 3rd and 4th electrode pair respectively. Open circuit voltage represents the maximum voltage that can be measured across each pair of electrode in the absence of external load and can therefore approach the overall electromotive force (E_{emf}), internal losses aside that could be achieved (Logan et al., 2006). Generally, imitations and losses lead to average OCVs which typically range from 300mv to 700mV (Logan, 2008). Considering the above relatively steady average performance from all four electrode pairs, cell performance seems promising for further developments.

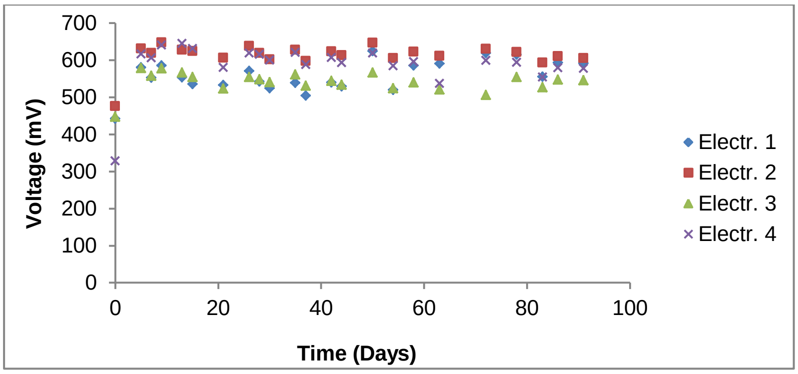

Figure 2: Open circuit voltage (OCV) generation from four electrode pairs in 100lt MFC

In addition to OCV short circuit current (SC) can be considered as the maximum current that can be instantly across the electrode pairs and the average achieved was 124±23mA, 133±23mA, 126±17 and 132±20mA for the 1st, 2nd, 3rd and 4th electrode pair respectively. Table 1 below summarises open circuit voltage, short circuit current and through Ohm's law average maximum power obtained from all four electrode pairs. Finally, maximum power was achieved in electrode 2 where the maximum OCV was 648mV with maximum SC 163mA producing 106mW power output.

Table 1: Average electrical characteristics of MFC in open circuit mode

	OCV (mV)	SC (mA)	P_{max} (mW)
1st electr.	558±42	124±23	70±15
2nd electr.	614±33	133±23	82±16
3rd electr.	542±28	126±17	69±11
4th electr.	589±62	132±20	79±16

3.2 COD removal efficiency

Considering a hydraulic retention time of four days, E_{COD} was monitored after the fifth day starting at almost 71% and immediately raising to approximately 96%. Over the 90 days monitoring period, E_{COD} only slightly fluctuated and stabilised at 90±6%. Minor fluctuations can be considered a result of fluctuating input. However, this only supports the advantages of creating a robust system that can effectively treat real time, continuous industrial wastewater. Finally, maximum removal efficiency of 97% was achieved.

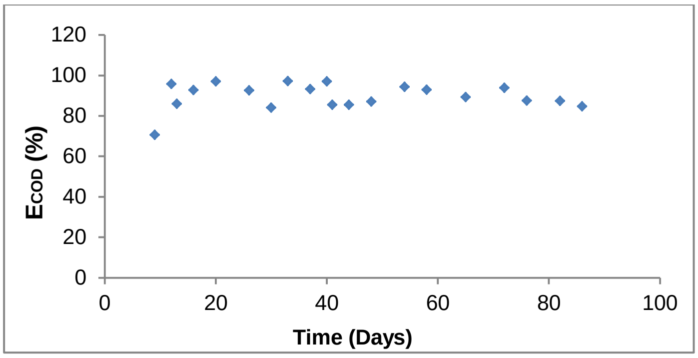

Figure 3: E_{COD}(%) from final MFC exit point

4. Conclusions

The current study was able to demonstrate successful COD removal efficiency and promising maximum power production from diluted spent wash, a relatively low strength whisky distillation process co-product. The 90 days trial demonstrated the robustness of the microbial community and presented a promising performance for higher volume wastewater.

Current and prospective studies focus on treating anaerobic digestion liquid digestate in order to enable determination of parameters affecting MFC operation and thus more accurately define and optimise the wastewater treatment performance and electricity generation in a large scale system. Moving from 170ml laboratory scale MFCs to a 100lt semi-technical unit demonstrated scalability and future work includes the development of a cascaded industrial system that can work either competitively or complementarily to existing wastewater treatment technologies.

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