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The influence of anodic helical design on fluid flow and bioelectrochemical performance

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HIGHLIGHTS

- Anodic helical design and flow characteristics influence MFC performance.
- High shear rates promote mixing and COD removal.
- Enrichment under shear conditions promotes biofilm development within the anode.
- Improved performance follows transition from laminar to turbulent flow.

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ABSTRACT

In this study three different tubular helical anode designs are compared, for each helical design the pitch and nominal sectional area/liquid flow channel between the helicoids was varied and this produced maximum power densities of 11.63, 9.2 and 6.73 W m^{-3} (small, medium and large helical flow channel cross-sections). It is found that the level of mixing and the associated shear rates present in the anodes affects both the power development and biofilm formation. The small helical flow channel carbon anode produced 40% more biofilm and this result was related to modelling data which determined a system shear rate of 237 s^{-1}, compared to 52 s^{-1} and 47 s^{-1} for the other reactor configurations. The results from computational fluid dynamic modelling further distinguishes between convective flow conditions and supports the influence of helical structure on system performance, so establishing the importance of anodic design on the overall electrogenic biofilm activity.

1. Introduction

Microbial fuel cell (MFC) technology continues to offer a promising means of harnessing electrical energy from organic waste streams whilst also providing a means of anaerobically treating a range of wastewaters (Logan et al., 2006; Rozendal et al., 2008). The future development of commercially viable bioelectrochemical systems (BES) requires an increase in power production along with the concurrent development of larger scalable reactor systems; however it is generally recognised that power densities tend to decrease as the reactor systems are scaled-up (Cusick et al., 2011). The technical development from laboratory based reactors to operational waste treatment systems requires a number of inherent electrochemical and biological bottle-necks to be addressed before BES reactors can become an economically viable alternative to current treatment technologies (Rozendal et al., 2008). A number of these factors have been found to significantly influence the performance of MFCs; notably aspects of reactor architecture, pH, conductivity, external loading, substrate type and temperature (Jadhav and Ghangrekar, 2009; Logan et al., 2006; Michie et al., 2011; Nama et al., 2010).

Continuous flow MFCs that utilise fixed anodic biofilms offer the best potential for cost-effective bioprocess treatment (Ieropoulos et al., 2010), and are less affected by dynamic environmental conditions that can develop in batch based systems. Continuous operation allows MFCs to be scaled up in hydraulically connected stacked units, this allows the levels of power recovery and organic removal to be increased by simply extending the number of reactor units (Kim et al., 2011). However, in order to maximise electro-biocatalytic activity it is necessary to increase the available surface area for microbial colonization whilst also optimizing the mass transfer of substrate into the biofilm and protons out of the biofilm. When BES systems are operated in batch or at low flow rates,

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diffusion of the substrate from the bulk solution through the boundary layer is the dominant mass transfer mechanism; under these conditions non-electrogenic biomass can accumulate which can lead to reduced anodic power production (Michie et al., 2011). Increasing the flow velocity increases the Reynolds numbers (*Re*) which leads to an increase in shear rates, levels of turbulence and a reduction in the boundary layer. Electrogenic biofilms subject to high shear during enrichment tend to be denser and have a reduced thickness (Pham et al., 2008), under these conditions it is likely that closer spatial proximity of the bacteria with the anode directly leads to improved electron transfer and biocatalytic activity. However, high flow velocities can also significantly increase shear stresses which will directly lead to biofilm detachment.

A number of studies have investigated the use of three dimensional carbon anode materials to improve current densities (Aelterman et al., 2008). Further work has also been carried out to look at forced flow through carbon anodes as a mechanism to enable forced convective flow (Sleutels et al., 2009), but this e strategy may have disadvantages when operating with real wastewaters due to the presence of particulates and the build-up of biofilm biomass which would result in restricted flows occurring over time. An alternative approach is to look at parametric design of anode morphology as a way of enhancing MFC performance. One approach that has been recently investigated is the use of spiral or helical channels to direct the flow in the anode chamber (Kim et al., 2012; Mahdi Mardanpour et al., 2012; Zhang et al., 2013). The use of these types of anodic designs has led to improved BES performance in terms of power density and COD removal, when using both artificial and real wastewater streams.

In order to further reduce over-potentials associated with mass transfer effects, decrease HRTs and increase the surface area available for biocatalyst attachment and activity, three different tubular helical anode reactors were constructed to test the influence of the flow characteristics within the different helical channels. For each helical anode the pitch or constructed gap/liquid flow channel between the helicoids was varied i.e. the carbon veil width. The changes in the physical parameters of the anode were designed to vary the hydrodynamic properties under continuous flow conditions, a spoke configuration in the polymer frame was used to support the textile anode material within the helix, but these also acted as periodic flow disrupters. The different hydraulic diameters and precession of the helix acted to change the relative velocities in the anode chamber; the sharp edged spokes instigated mixing and sought to increase the degree of turbulent flow and mixing characteristics. To investigate this influence, the three different helical anodes were operated over a range of flow rates and at two different organic loading rates. The effect of the helical design on the microbial community development and the level of biofilm growth within the three dimensional carbon veil electrode were assessed in conjunction with computational fluid dynamic (CFD) modelling applied to the three different anodic geometries.

2. Methods

2.1. MFC reactor manufacture and operation

Single chamber air cathode tubular MFC reactors (280 mm long and 40 mm diameter) were constructed using polypropylene tubing. An air cathode (80 × 210 mm) with 0.5 mg/cm^2 platinum catalyst loading was prepared with activated carbon and this was then combined with a cation exchange membrane (CMI-7000, Membrane International Inc. NJ, USA), this membrane assembly was then sited on the outside of the polypropylene tubing support.

The reactors were inoculated with a 10% anaerobic digestion sludge (Cog Moors wastewater treatment plant, Cardiff, Wales) consisting of 24.5 ml sludge in 220.5 ml of substrate media, this media was formulated with 50 mM phosphate buffer (pH 7.0) with added vitamin/minerals solution and 40 mM sodium acetate. The systems were initially enriched in batch mode, with each reactor connected independently to an external resistive load circuit (1000 Ω) and the voltages across the MFCs were recorded at 10 min intervals using LabVIEW™ software and a NI 16-Bit, isolated M Series MIO DAQ, (National Instrument Corporation Ltd. Berkshire UK). The substrate was fed weekly for a period of 4 weeks, at which point all the MFC reactors had reached a steady-state voltage 0.42 V (±0.02 V) and the systems were converted to continuous operation for a period of 2 weeks at a set flow rate of 20 ml min^{-1}. The flow rates in the reactors were then sequentially increased in steps (10, 30, 70, 135, 270 and 540 ml min^{-1}), testing was carried out at each flow rate once steady state operation in the system had been observed. When operating in continuous mode, 4 channel peristaltic pumps (Watson and Marlow, Falmouth, UK) were used to deliver the substrate to the reactors, at each set flow rate the pumps were first calibrated using new peristaltic tubing. Whilst operating continuously the media was supplied from storage vessels that were maintained at 4 °C, these vessels were first purged with nitrogen to prevent oxygen contamination and refrigerated to 4 °C to prevent the growth of microbial contaminants.

2.2. Helical anode design and construction

Three different helical anode supports were designed and modelled using SolidWorks 3D CAD software (Waltham, MA, USA). The helical support modules were manufactured from polymeric (ABS) material and constructed with inner and outer helices which extended to the full diameter of the anode chamber from a cylindrical core, the helices were supported/connected by spokes. The pitch and average cross sectional area of the flow channel was varied between these modules; the spacing between helices was Helix 1 (SP1) 1.5 mm, Helix 2 (SP2) 5.4 mm and Helix 3 (SP3) 10.8 mm, respectively. The anode structures were then constructed from the CAD solid model using a Dimension 3D 1200es printer (Stratasys, Mn, USA). Carbon veil cloth (PRF Composite Materials, Dorset, UK) of 17, 13 and 10 mm widths were then each wrapped into the different helical reactor anode formers of the SP1, SP2 and SP3 anodes, respectively, a Perspex mounting rod was inserted into the centre of the anodes to provide structural support. The MFC reactors were then sealed to ensure water integrity, giving final liquid reactor volumes of 147, 177 and 202 ml, respectively. A strip of stainless steel mesh (Type 304, Lenntech BV, Netherlands) was cut to the respective widths and laid on top of the anode material in order to compact and hold the carbon veil beneath, the steel mesh also acted as an electrical current collector.

2.3. Analyses

2.3.1. Electrochemical and chemical analysis

Measurement and calculation of power production and coulombic efficiency (CE) measurements for all reactor operations were carried out as previously described (Logan et al., 2006), with power production being determined using a potentiostatic method utilising a Solartron Electrochemical Interface (Farnborough, UK) and dedicated software (CorrWare 2™, Scribner Associate Inc., NC). A constant potential was applied over a range of 600–25 mV at 25 mV intervals and the current was then measured as a function of time (Kim et al., 2009). Liquid samples were taken from the reactors and then centrifuged at 12,000 rpm (16,060*g*) for 5 min, these were then tested directly or were first acidified (HCl, 12 M) and preserved frozen at −20 °C for future analysis. Soluble COD (sCOD)

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