Recent developments in microbial fuel cells: a review

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Received 26 March 2010; revised 23 July 2010; accepted 26 July 2010

This review presents microbial fuel cells (MFCs) that convert biochemical metabolic energy into electrical energy. Microbes can be fed with waste products rich in organic matter (domestic wastewater, lignocellulosic biomass, brewery wastewater, starch processing wastewater, landfill leachates etc.) to generate electricity. MFCs can also be used for wastewater treatment, as biosensors and production of secondary fuels like hydrogen.

Keywords: Biosensors, ETC, MFCs, Wastewater treatment

Introduction

Microbial fuel cells (MFCs) employ microbes to generate electricity from biochemical energy produced during metabolism of organic substrates. MFC consists of anode and cathode connected by an external circuit and separated by proton exchange membrane (PEM). In anode chamber, decomposition of organic substrates by microbes generates electrons (e-) and protons (H+) that are transferred to cathode through circuit and membrane respectively. Organic substrates are utilized by microbes as their energy sources, outcome of this process is in release of high-energy electrons that are transferred to electron acceptors (molecular oxygen) but in absence of such electron acceptor in a MFC, microorganisms shuttle electron onto anode surface that results in generation of electricity. Bacteria are most preferred microbes that can be used in MFCs to generate electricity while accomplishing biodegradation of organic matters or wastes. Biodegradable organic rich waters (municipal solid waste, industrial and agriculture wastewaters) are ideal candidates of sustainable energy sources for electricity production. MFCs can also be used as biosensors and in secondary fuel production.

This paper reviews recent developments in MFC technology highlighting working principle and applications of MFC technology.

MFCs: Setup and Working Principle for Electricity Generation

Basic Machinery

An ideal MFC apparatus (Fig. 1) consists of two chambers (anodic and cathodic) made up of glass, polycarbonate or Plexiglas, with respective electrode of graphite, graphite felt, carbon paper, carbon-cloth, Pt, Pt black or reticulated vitreous carbon (RVC). These chambers are separated by PEM (Nafion or Ultrex). Anodic chamber is filled with organic substrates that are metabolized by microbes for growth and energy production while generating electron and proton. Cathode is filled with a high potential electron acceptor to complete circuit. An ideal electron acceptor should not interfere with microbes in any way and must be a sustainable compound with no toxic effect. Oxygen serves as an ideal electron acceptor due to its non-toxic effect and preferred as oxidizing reagent as it simplifies operation of an MFC, otherwise standard media with suitable electron acceptor such as ferricyanid can also be used to increase power density. Based upon assembly of anode and cathode chambers, a simple MFC prototype can either be a double chambered or single chambered. Besides these two common designs, several adaptations have been made in prototype of MFC design and structure.

Double Compartment MFC System

In general, this type of MFCs has an anodic and a cathodic chamber connected by a PEM that mediates...
proton transfer from anode to cathode while blocking diffusion of oxygen into anode. This type of system is generally used for waste treatment with simultaneous power generation. Scaling up of two compartment MFCs to industrial size is quite tough. Moreover periodic aeration of cathodic chambers also limits application spectrum of double compartment MFCs.

Single Compartment MFC System

In a single compartment MFC, an anodic chamber is linked to a porous air exposed cathode separated by a gas diffusion layer or a PEM. Electrons are transferred to porous cathode to complete circuit. Limited requirement of periodic recharging with an oxidative media and aeration makes single compartment microbial fuel cell system more versatile. Among different advantages, single compartment MFC includes its reduced setup costs (due to absence of expensive membranes and cathodic chambers) that make flexible application in wastewater treatment and power generation.

Working Principle

MFC explores metabolic potential of microbes for conversion of organic substrate into electricity by transferring electrons from cell to circuit. In anodic chamber, oxidation of substrate in the absence of oxygen by respiratory bacteria produce electron and proton that are passed onto terminal $e^-$ acceptor [$O_2$, nitrate or Fe (III)] through electron transport chain (ETC) (Fig. 2). However, in absence of $e^-$ acceptor in a MFC, some microorganisms pass electron onto anode either by a spontaneous (direct) or by means of some electron shuttling mediators. Direct electron transfer to anode by bacteria requires some physical contact with electrode for current generation. Plunge line up between bacteria and anode surface involves outer membrane bound cytochromes or putative conductive pili called nanowires. These mediator-less MFCs often utilize anodiphiles to form a biofilm on anode surface to make easy use of anode as their end terminal electron acceptor in anaerobic respiration.

In mediated electron transfer machinery, microbes produce / acquire indigenous soluble redox compounds (quinones and flavin) or synthetic exogenous mediators (dye or metalloorganics) to shuttle electron between terminal respiratory enzyme and anode surface. These mediators can divert electrons from respiratory chain by entering outer cell membrane, becoming reduced, and then leaving in a reduced state to shuttle electron to electrode. Numbers of electron and proton fabricated depends upon substrate utilized by microbes. Mediator-less MFCs have more commercial potential as mediators are expensive and are sometimes toxic to microorganisms. Electrode reactions in a MFC compartments are as follows:

i) If acetate is used as substrate

**microbes**

Anodic reaction: $\text{CH}_3\text{COO}^- + \text{H}_2\text{O} \rightarrow 2\text{CO}_2 + 2\text{H}^+ + 8e^-$

Cathodic reaction: $\text{O}_2 + 4e^- + 4\text{H}^+ \rightarrow 2\text{H}_2\text{O}$

ii) If sucrose is used as substrate

**microbes**

Anodic reaction: $\text{C}_{12}\text{H}_{22}\text{O}_{11} + 13\text{H}_2\text{O} \rightarrow 12\text{CO}_2 + 48\text{H}^+ + 48e^-$

Cathodic reaction: $\text{O}_2 + 4e^- + 4\text{H}^+ \rightarrow 2\text{H}_2\text{O}$
Substrate used for Electricity Generation

Substrate is a key factor for efficient production of electricity from a MFC. Substrate spectrum used for electricity generation ranges from simple to complex mixture of organic matter present in wastewater. Although substrate rich in complex organic content helps in growth of diverse active microbes but simple substrates considered to be good for immediate productive output. Acetate and glucose are most preferred substrate for basic MFC operations and electricity generation. Lignocellulosic biomass from agriculture residues as hydrolysis products (monosaccharides) are a good source for electricity production in MFCs. Lignocellulosic biomass from agriculture residues as hydrolysis products (monosaccharides) are a good source for electricity production in MFCs. Another promising and most preferred unusual substrate used in MFCs operations for power generation is brewery wastewater as it is supplemented with growth promoting organic matter and devoid of inhibitory substances. Starch processing water can be used to develop microbial consortium in MFCs. Cellulose and chitin (from industrial and municipal wastewaters), synthetic or chemical wastewater, dye wastewater and landfill leachates are some unconventional substrates used for electricity production via MFCs.

Commonly used Microbes in Microbial Fuel Cells (MFCs)

Usually mixed culture of microbes is used for anaerobic digestion of substrate as complex mixed culture permits broad substrate utilization. But there are some regular MFCs designs which explore metabolic tendency of single microbial species to generate electricity. Organic component rich sources (marine sediment, soil, wastewater, fresh water sediment and activated sludge) are rich source of microbes that can be used in MFCs catalytic unit. Bacteria used in MFCs with mediator or without mediators have been extensively studied and reviewed (Table 1). Metal reducing and anodophilic microorganisms show better opportunities for mediator-less operation of a MFC.

Other Applications
Wastewater Treatment and Electricity Generation

Due to unique metabolic assets of microbes, variety of microorganisms are used in MFCs either single species or consortia. Some substrates (sanitary wastes, food processing wastewater, swine wastewater and corn stovers) are exceptionally loaded with organic matter that itself feed wide range of microbes used in MFCs. MFCs using certain microbes have a special ability to remove sulfides as required in wastewater treatment. MFC substrates have huge content of growth promoters that can enhance growth of bio-electrochemically active microbes during wastewater treatment. This

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**Table 1**—Commonly used bacteria in MFCs

<table>
<thead>
<tr>
<th>Bacteria</th>
<th>Mode of operation</th>
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<tbody>
<tr>
<td><em>Actinobacillus succinogenes</em></td>
<td>Requires exogenous mediators</td>
</tr>
<tr>
<td><em>Erwinia dissolven</em></td>
<td>Mediator based MFC</td>
</tr>
<tr>
<td><em>Proteus mirabilis</em></td>
<td>Mediator based</td>
</tr>
<tr>
<td><em>Pseudomonas aeruginosa</em></td>
<td>With exogenous mediators</td>
</tr>
<tr>
<td><em>Shewanella oneidensis</em></td>
<td>With exogenous mediators</td>
</tr>
<tr>
<td><em>Streptococcus lactis</em></td>
<td>With mediators</td>
</tr>
<tr>
<td><em>Aeromonas hydrophilia</em></td>
<td>Mediator-less MFC</td>
</tr>
<tr>
<td><em>Geobacter metallireducens</em></td>
<td>Mediator-less MFC</td>
</tr>
<tr>
<td><em>G. sulfurreducens</em></td>
<td>Mediator-less MFC</td>
</tr>
<tr>
<td><em>Rhodoferax ferrireducens</em></td>
<td>Mediator-less MFC</td>
</tr>
<tr>
<td><em>Shewanella putrefaciens</em></td>
<td>Mediators-less MFC, Exogenous mediators improve electricity production</td>
</tr>
<tr>
<td><em>Klebsiella pneumoniae</em></td>
<td>Mediator based</td>
</tr>
</tbody>
</table>

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Fig. 2—Electron shuttling mechanism in a MFC
simultaneous operation not only reduces energy demand on treatment plant but also reduces amount of unfeasible sludge produce by existing anaerobic production. MFCs connected in series have high level of removal efficiency to treat leachate with supplementary benefit of generating electricity.

**Biosensors**

MFCs with replaceable anaerobic consortium could be used as a biosensor for on-line monitoring of organic matter. Though diverse conventional methods are used to calculate organic content in term of biological oxygen demand (BOD) in wastewater, most of them are unsuitable for on-line monitoring and control of biological wastewater treatment processes. A linear correlation between Coulombic yield of MFC and strength of organic matter in wastewater makes MFC a possible BOD sensor. Coulombic yield of MFC provides an idea about BOD of liquid stream that proves to be an accurate method to measure BOD value at quite wide concentration range of organic matter in waste water.

**Secondary Fuel Production**

With minor modification, MFCs can be employed to produce secondary fuels like hydrogen (H\(_2\)) as an alternative of electricity. Under standard experimental conditions, proton and electron produced in anodic chamber get transferred to cathode, which then combines with oxygen to form water. H\(_2\) generation is thermodynamically not favored or it is a harsh process for a cell to convert proton and electron into H\(_2\). Increase in external potential applied at cathode can be competent to overcome thermodynamic barrier in reaction and used for H\(_2\) generation. As a result, proton and electron produced in anodic reaction chamber combine at cathode to form H\(_2\). MFCs can probably produce extra H\(_2\) as compared to quantity that pull off from classical glucose fermentation method. Wagner et al. reported H\(_2\) and methane production by using microbial electrolytic cells that are modified MFC with increased external potential at cathode. Thus, MFCs provide a renewable H\(_2\) to contribute to overall H\(_2\) demand in a H\(_2\) economy.

**Advancement in MFC Technology**

Development of MFCs was triggered by USA space program in 1960s as a possible technology for a waste disposal system for space flights that would also generate power. MFC technology has been extensively reviewed focusing on recent improvement, practical implementation, anode performance, cathodic limitations, different substrates used in MFCs etc. MFCs have been explored as a new source of electricity generation during operational waste treatment. In addition, some of the recent modification in MFC technology includes its use as microbial electrolysis cell (MEC), in which anoxic cathode is used with increased external potential at cathode. Phototrophic MFCs and solar powered MFC also represent an exceptional attempt in the progress of MFCs technology for electricity production.

**Conclusions**

MFC is an ideal way of generating electricity since it not only as a renewable source but also can be used to treat waste. It can also be used for production of secondary fuel as well as in bioremediation of toxic compounds. However, this technology is only in research stage and more research is required before domestic MFCs can be made available for commercialization.

**References**


