

Evolution of Microbial Fuel Cell as a Promising Technology for Waste Water Treatment

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Abstract- Attributed to exponentially growing global energy demand in current scenario, Microbial Fuel Cell (MFC) is an attempt aimed towards achieving integrated water and energy sustainability. MFC acts a bioelectrochemical reactor (system) that utilizes the ability of microorganisms to destabilize organic compounds present in wastewater, of domestic or industrial origin, resulting in breakdown of these compounds into simpler forms coupled with generation of electricity. This imparts MFC, status of a biofuel cell, which has clear advantages of operation at mild reaction conditions, cost effective and biotechnology based wastewater treatment with reduced sludge formation coupled with energy generation over chemical fuel cells that use highly reactive fuels and severe operating conditions. This paper aims at reviewing timely developments in Microbial Fuel Cell Technology with emphasis on its application in the area of effluent treatment clubbed with the potential for electricity generation. If power generation in MFC can be increased, this technology may provide a new method to offset wastewater treatment plant operating costs, with less excess sludge production.

Keywords: Microbial Fuel Cell, Microorganism, Waste Water Treatment, Electricity generation

I. INTRODUCTION

Microbial fuel cell (MFCs) have emerged in recent years as a promising yet challenging technology. MFCs are the major type of bioelectrochemical systems (BESs) which convert biomass spontaneously into electricity through the metabolic activity of the microorganisms. MFC is considered to be a promising sustainable technology to meet increasing energy needs, especially using wastewaters as substrates, which can generate electricity and accomplish wastewater treatment simultaneously.

Electricity has been generated in MFCs from various organic compounds including Carbohydrates, proteins and fatty acids. One of the greatest advantages

of MFCs over conventional fuel cells like hydrogen and methanol fuel cell is that a diverse range of organic material can be used as fuels.

A typical MFC consists of anode and cathode separated by a cation specific membrane. Microbes in the anode oxidize fuel/substrate and gain energy for metabolism by transferring electrons from an electron donor, such as glucose or acetate to an electron acceptor such as oxygen and the resulting electrons and protons are transferred to cathode through the circuit and the membrane respectively. Electrons and protons are consumed in the cathode, reducing oxidant usually oxygen. Since the microbial cells are electrochemically inactive due to nonconductive cell surfaces structure, mediators are employed to facilitate electron transfer from the microbial cells to the anode in MFCs.

Application of MFCs for wastewater treatment is very attractive due to energy recovery from waste as well as reducing production of excess sludge, disposal of which is very expensive. It is expected that this process would generate much less excess sludge than a conventional activated sludge process, since the major part of energy available from the oxidation of the organic contaminants is converted to electricity, and the remaining energy is used for microbial growth.

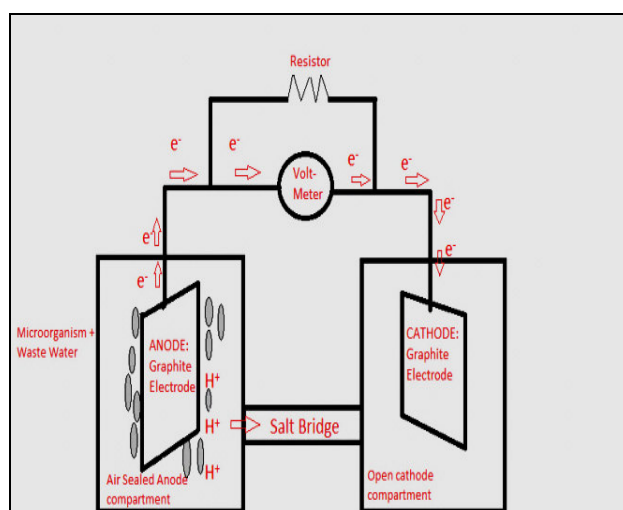


Fig.1 Operating principle of MFC.

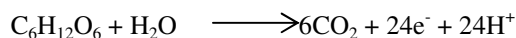
II. HISTORY OF MICROBIAL FUEL CELL DEVELOPMENT

Theoretically, most microbes can potentially be used as a biocatalyst in MFC. The earliest MFC concept was demonstrated by Potter in 1910. Electrical energy was produced from living cultures of *Escherichia Coli* and *Saccharomyces* by using platinum electrodes. This didn't generate much interest until 1980s when it was discovered that current density and the power output could be greatly enhanced by the addition of electron mediators. Unless the species in the anodic chamber are anodophiles, the microbes are incapable of transferring electrons directly to the anode. The outer layers of the majority of microbial species are composed of non-conductive lipid membrane, peptidoglycans and lipopolysaccharides that hinder the direct electron transfer to the anode.

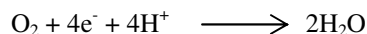
Electron mediators accelerate the transfer. Mediators in an oxidized state can easily be reduced by capturing the electrons from within the membrane. The mediators then move across the membrane and release the electrons to the anode and become oxidized again in the bulk solution in the anodic chamber. This cyclic process accelerates the electron transfer rate and thus increases the power output. Good mediators should possess the following features: (1) able to cross the cell membrane easily; (2) able to grab electrons from the electron carriers of the electron transport chains; (3) possess a high electrode reaction rate; (4) have a good solubility in the anolyte; (5) nonbiodegradable and non-toxic to microbes; (6) low cost and how efficient the oxidized mediator gets reduced by the cells reducing power is more important compared with other features.

Typical electrode reactions are shown below using glucose as a fuel example.[5]

Anodic reaction:



Cathodic reaction:



III. MICROBES USED IN MICROBIAL FUEL CELLS

Many microorganisms possess the ability to transfer the electrons derived from the metabolism of organic matters to the anode. A list of them is shown in Table 1 together with their substrates. Marine sediment, soil, wastewater, fresh water sediment and activated sludge are all rich sources for these microorganisms. A number of recent publications discussed the screening and identification of microbes and the construction of a chromosome library for microorganisms that are able to generate electricity from degrading organic matters.

The anodic electron transfer mechanism in MFC is a key issue in understanding the theory of how MFCs

work. *Geobacter* belongs to dissimilatory metal reducing microorganisms, which produce biologically useful energy in the form of ATP during the dissimilatory reduction of metal oxides under anaerobic conditions in soils and sediments. The electrons are transferred to the final electron acceptor such as Fe_2O mainly by a direct contact of mineral oxides and the metal reducing microorganisms.

The anodic reaction in mediator-less MFCs constructed with metal reducing bacteria belonging primarily to the families of *Shewanella*, *Rhodospirillum rubrum*, and *Geobacter* is similar to that in this process because the anode acts as the final electron acceptor just like the solid mineral oxides. The mediators then transfer across the membrane and release the electrons to the electrode and become oxidized again in anodic chamber and thus are reutilized.

Anodophilic bacteria from different evolutionary lineages from the families of *Geobacteraceae*, *Desulfuromonadaceae*, *Pasteurellaceae*, *Clostridiaceae*, were able to transfer electrons to electrodes. The overall limiting steps to enhance the power production are showed in the Fig 2. The main disadvantage of a two chamber MFC is that the solution cathode must be aerated to provide oxygen to the cathode.

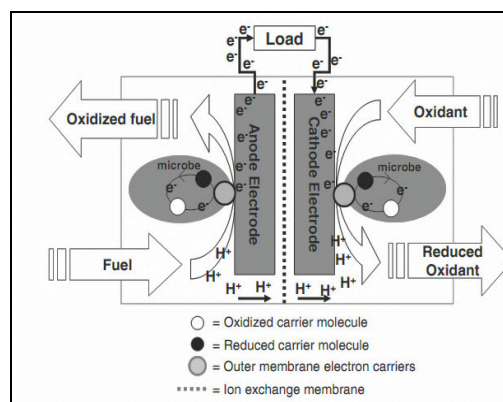


Fig 2: Microbial fuel cell schematic for wastewater management[10]

IV. DESIGN OF MICROBIAL FUEL CELL

1) Double chamber MFC system

Two-compartment MFCs are typically run in batch mode often with a chemically defined medium such as glucose or acetate solution to generate energy. They are currently used only in laboratories.

A typical two compartment MFC has an anodic chamber and a cathodic chamber connected by a PEM, or sometimes a salt bridge, to allow protons to move across to the cathode while blocking the diffusion of oxygen into the anode.

TABLE 1
MICROORGANISMS USED IN MICROBIAL FUEL CELL (MFC)

MICROORGANISMS	SUBSTRATES	MEDIATORS	REFERENCES
Saccharomycescerevisiae	Hydrolyzed Lactose	MB,NR	[23]
Escherichia coli	Glucose	NR	[24]
Enterobactercloacae	Glucose	Methyl Viologen, MB	[1]
Saccharomycescerevisiae	Glucose	Resorufin	[25]
Aeromonashydrophila	Glucose, Acetate	Without mediator	[26]
Enterococcusfaecium	Glucose	Pyocyanin	[27]
Streptococcus lactis	Glucose	Ferric Chelate complex	[28]
Proteus vulgaris	Glucose,Maltose,Galactose	Thionin	[29]
Shewanella putrefaciens	Lactate	Without mediator	[30]
Rhodoferrax ferrireducens	Glucose	Without mediator	[31]
Activated sludge	Wastewater	Without mediator	[32]
Mixed consortium	Glucose, Sucrose	Without mediator	[33]
Actinobacillusuccinogenes	Glucose	NR,Thionine	[34]
Klebsiellapneumoniae	Glucose	HNQ	[35]
Micrococcus luteus	Glucose	Thionine	[36]
Shewanellaoneidensis	Lactate	Anthraquinone-2,6-	[37]
Escherichia coli	Glucose, Acetate	disulfonate(AQDS) NR, 2-	[37-40]
Proteus vulgaris	Glucose, Sucrose	Hydroxy-1,4-Naphthoquinone, MB Thionine	[41-44]
Shewanella putrefaciens	Lactate, Pyruvate, Acetate	NR	[45]
Proteus mirabilis	Glucose	Thionine	[46]
Shewanella putrefaciens	Glucose, Lactate	Without mediator	[30]

The compartments can take various practical shapes. The schematic diagrams of five two-compartment MFCs are shown in Fig. 3. The mini-MFC shown in Fig. 3C having a diameter of about 2 cm, but with a high volume power density was reported by Ringeisen et al.[37]. They can be useful in powering autonomous sensors for long-term operations in less accessible regions. On the other hand, fluid recirculation is used in both cases. The energy costs of pumping fluid around are much greater than their power outputs. Therefore, their primary function is not power generation, but rather wastewater treatment.

Min and Logan designed a Flat Plate MFC (FPMFC) with only a single electrode/PEM assembly. [20]. Its compact configuration resembles

that of a conventional chemical fuel cell. A carbon-cloth cathode that was hot pressed to a Nafion PEM is in contact with a single sheet of carbon paper that serves as an anode to form an electrode/PEM assembly.

The FPMFC with two non-conductive polycarbonate plates is bolted together. The PEM links the anodic and the cathodic chambers. The anodic chamber can be fed with wastewater or other organic biomass and dry air can be pumped through the cathodic chamber without any liquid catholyte, both in a continuous flow mode.

2) Single chamber MFC system

Due to their complex designs, two-compartment MFCs are difficult to scale-up even though they can

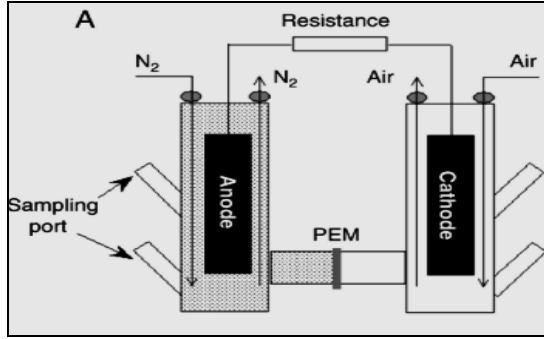


Fig.3 (a) Cylindrical shape

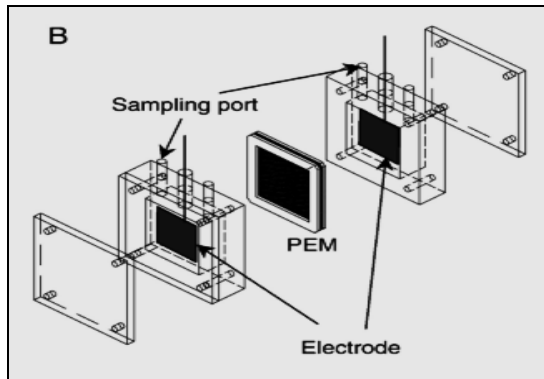


Fig.3 (b) Rectangular shape

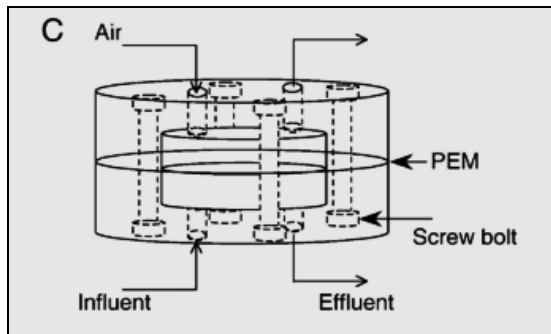


Fig.3 (c) Miniature shape

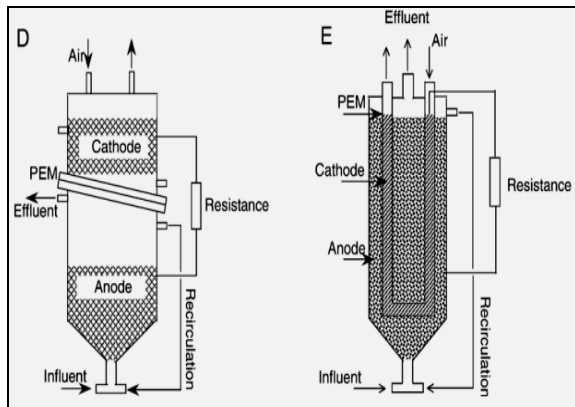


Fig.3 (d) Up flow configuration with cylindrical shape

Fig.3. Schematics of a two-chamber MFC [4]

be operated in either batch or continuous mode. One compartment MFCs offer simpler designs and cost savings. They typically possess only an anodic chamber without the requirement of aeration in a cathodic chamber. Park and Zeikus designed a one compartment MFC consisting of an anode in a rectangular anode chamber coupled with a porous air-cathode that is exposed directly to the air as shown in Fig. 4(a). Protons are transferred from the anolyte solution to the porous air-cathode. Liu and Logan designed an MFC consisting of an anode placed inside a plastic cylindrical chamber and a cathode placed outside. Fig.4 (b) shows the schematic of a laboratory prototype of the MFC bioreactor. The anode was made of carbon paper without wet proofing. The cathode was either a carbon electrode/PEM assembly fabricated by bonding the PEM directly onto a flexible carbon-cloth electrode.

There are many other types of MFCs have developed in recent years as the advancement of technology to improve the power density. Table 2 shows the main basic components of MFC.

1. Two-Chamber MFC system
2. Single Chamber system
3. Up-flow mode MFC systems
4. Stacked MFC

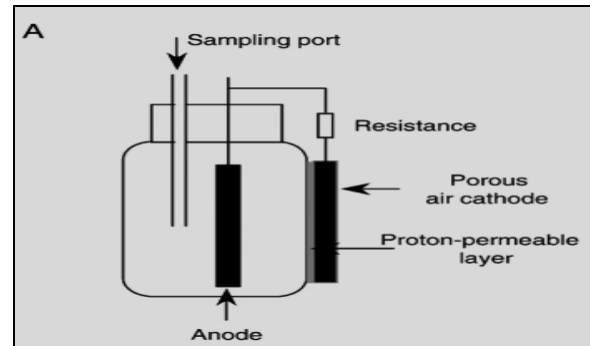


Fig 4 (a): MFC with a proton permeable layer coating the inside of the window-mounted cathode

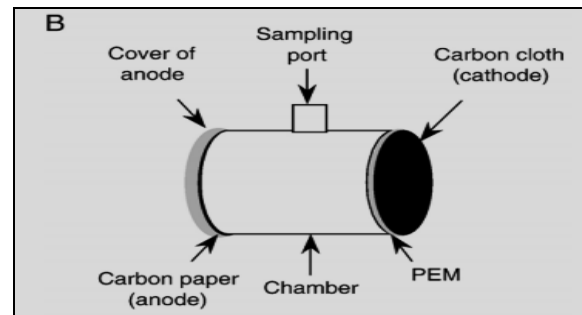


Fig 4 (b): MFC consisting of an anode and cathode placed on opposite side in a plastic cylindrical chamber.

Fig 4.Single chamber MFC[4]

TABLE 2
BASIC COMPONENTS OF MFC[5]

Items	Materials	Remarks
Anode	Graphite, Carbon paper, Carbon cloth, Pt, Pt black	Necessary
Cathode	Graphite, Carbon paper, Carbon cloth, Pt, Pt black	Necessary
Anodic chamber	Glass, Plexi glass, Polycarbonate	Necessary
Cathodic chamber	Glass, Plexi glass, Polycarbonate	Optional
Proton Exchange Membrane	PEM: Nafionultrex, salt bridge, porcelain septum	Necessary
Electrode catalyst	Pt, Pt black, $\text{MnO}_2\text{Fe}^{3+}$,	Optional

V. FACTORS AFFECTING MFC EFFICIENCY

1) Electrode Material

There are different types of electrode material used for increasing the efficiency for the MFC. The Type of material used in electrode preparation will show vital effect on MFCs efficiency. Better performing electrode materials usage will always improve the performance of MFC because different anode materials result in different activation polarization losses. Pt and Pt black electrodes are superior to graphite, graphite felt and carbon-cloth electrodes for both anode and cathode constructions, but their costs are much higher. Schroder et al. reported that a current of 2–4 mA could be achieved with platinumized carbon-cloth anode in an agitated anaerobic culture of *E. coli* using a standard glucose medium at 0.55 mmol/L. Pt also has a higher catalytic activity with regard to oxygen than graphite materials. MFCs with Pt or Pt-coated cathodes yielded higher power densities than those with graphite or graphite felt cathodes. [34, 35]

2) pH Buffer and Electrolyte

If no buffer solution is used in a working MFC, there will be an obvious pH difference between the anodic and cathodic chambers, though theoretically there will be no pH shift when the reaction rate of protons, electrons and oxygen at the cathode equals the production rate of protons at the anode. The PEM causes transport barrier to the cross membrane diffusion of the protons, and proton transport through the membrane is

slower than its production rate in the anode and its consumption rate in the cathode chambers at initial stage of MFC operation thus brings a pH difference. [36]

However, the pH difference increases the driving force of the proton diffusion from the anode to the cathode chamber and finally a dynamic equilibrium forms. Some protons generated with the biodegradation of the organic substrate transferred to the cathodic chamber are able to react with the dissolved oxygen while some protons are accumulated in the anodic chamber when they do not transfer across the PEM or salt bridge quickly enough to the cathodic chamber. Increasing ionic strength by adding NaCl to MFCs also improved the power output [37] possibly due to the fact that NaCl enhanced the conductivity of both by anolyte and the catholyte.

3) Proton Exchange System

Proton exchange system can affect an MFC system's internal resistance and concentration polarization loss and they in turn influence the power output of the MFC. Nafion (DuPont, Wilmington, Delaware) is most popular because of its highly selective permeability of protons. However, side effect of other cations transport is unavoidable during the MFC operation with Nafion. But its usage is better in the sense of charge balance between the anodic and cathodic chambers. Hence Nafion as well as other PEMs used in the MFCs are not a necessarily proton specific membranes but actually cation specific membranes. The ratio of PEM surface area to system volume is important for the power output. The MFC internal resistance decreases with the increase of PEM surface area over a relatively large range.[38]

VI. CONCLUSION

At present the field of MFCs is in its infancy and also this is an exciting time in microbial fuel cell research. The MFCs technology has evolved to compete with well advanced methanogenesis technology where biomass is used as substrate. In contrast to methanogenesis MFCs are capable to convert biomass to electricity at low temperatures and substrate concentration. The discovery and usage of new anodophilic microbes that vastly enhance the electron transport rate from the biofilm covering an anode to the anode are much needed to improve the power density output in MFCs.

The ultimate achievement in for MFCs will be when they can be used solely as a method of renewable energy production. Right now, the high

costs of materials for MFCs and the relatively cheap price of fossil fuels makes it unlikely that electricity production can be competitive with existing energy production methods. Microbial fuel cell is one of the most upcoming technologies for power generation and is being developed so as to obtain a consistent high power.

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