A review on microbial fuel cells (MFCs)

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Abstract

Microbial fuel cell directly converts chemical energy to electrical energy through catalytic reactions using bacteria and microbes. Due to decline of fossil fuels ,the necessity of replacing present energy source with an economical, clean and renewable type has been felt completely. Microbial fuel cells are capable to use biomass, a renewable type of energy source to generate electricity. They also have been applied specially in food processing industries for wastewater treatment. MFC can work as biosensor for control of oxygen biological requirements. Additionally Using MFC is a new method for generating hydrogen from organic matter metabolisms. This paper is a general review of recent research advances in the configuration and performance of Microbial fuel cell which hopes to highlight some important points regarding the recent advances.

Keywords: microbial fuel cell (MFC); Wastewater treatment; Electricity generation; Biosensor

1. *Introduction*

Nowadays due to the growing rate of increasing population and industrial improvements, energy demanding drastically has gone up. It is obvious that Current reliance on fossil fuels is unreasonable due to pollution and finite supplies. In this situation finding new, clean, economical and sustainable sources of energy has become a big worldwide challenge.

At the present time much research is being done to find new energy solutions. Concerning high rate of energy use, it appears that none of new energy sources will be able to replace fossil fuels absolutely. Developments on MFC technology are very hopeful; this technology might be a real solution for bringing to an end the energy crisis and global warming problem. Around one hundred years ago for the first time M.C. potter presented the idea of using microbial fuel cell to generate electricity [1].

A microbial fuel cell (MFC) is a system that drives a current by converting chemical energy to electrical energy, using the microorganisms. An MFC consists of an anode, a cathode, and to separate these it needs a membrane. In anode side there is some kinds of bacteria which degrade organic materials. Released electrons move to cathode by an external circuit. Keeping balance the system, protons as well go to cathodes trough a membrane. The result of this electron transfer is an electrical current. As a matter of fact MFCs work the same as other types of fuel cells other than they use some kinds of degradable chemicals as the fuel. MFCs could be classified to two different types of Mediator and mediator-less Microbial Cells. Mediator Microbial Fuel Cells are inactive which they need mediators for electron transferring. The mediator-less microbial fuel cell does not require a mediator but uses some types of bacteria to transfer electrons to the electrode [2].

One of the most common applications of MFCs rather than generating electricity is wastewater treatment. Industrial, Sanitary and food processing wastewater which includes hydrocarbons can be used as the fuel for MFCs Actually organic materials in waste water used by some kinds of bacteria which exist in MFCs.

These systems are enough flexible regarding their kinds of fuel, have high efficiency and can work for years without need to be charged again.

The importance of review articles to inform others about the latest achievements is undeniable. Therefore this article hopes to briefly review the roles and importance of current microbial fuel cells. However, it is unable to cover total field of MFC research but wishes to highlight some important points regarding the recent advances.

2. *History of microbial fuel cell development*

At the end of recent century, the idea of using microbial cells was presented as a sustainable way to generate electricity [14]. As a matter of fact M.C. Potter, Botanical Professor at the University

of Durham, was the first person who began study on microbial cell since 1911[14]. He intended to generate electricity from E. coli. In 1931, Branet Cohen continued Potter’s work by employing some semi microbial fuel cell in a series form which had only the production capacity of 35 volts and two milliampere flows [15].Regarding thatmore activity was done by Del Duca et al. They apply hydrogen which was produced from glucose fermentation using Clostridium butyricum as the reactive material in fuel cell anode [16]. But it was not reliable enough due to the unstable nature of microorganisms, in hydrogen production however this problem was solved by Suzuki et al In 1976[17,18].Even after Suzuki's efforts, a few details of fuel cell performance was achieved until complementary studies was done by the MJ Allen and H. Peter Benetto both from King College London. As a matter of fact Bennetto was considered fuel cell as a method of generating electricity for developing countries. He started his work in early 1980s, And his finding did a remarkable help to understand how fuel cells work[19].

New discoveries indicate that electricity can be directly generated from organic material decomposition in a fuel cell although the exact mechanism is not clarified in detail. In May 2007, at Queen Sland University in Australia, the MFC experimental samples be completed as a joint project with the company Fosters Brewing. The experimental samples, with volume 10 L fermentation plant wastewater into practice to carbon dioxide, clean water and electricity. In Isfahan University of Technology Dr. Ali Akbar Dadkhah with using silver nanoparticles could increase efficiency at Katvlyt microbial fuel cell with different concentrations. All the tests conducted on two different electrodes with carbon cloth and carbon paper material, has increased electric current can be up to 19 percent and power 29 percent compared to net Katvlyt (without nanoparticles).

3. Overall view of Fuel cell

Fuel cell is a kind of electrochemical cell which directly converts chemical energy released from the reaction to electrical energy .The main body of fuel cell consists of anode, cathode, andelectrolyte solution. Following figure presented the overall view of a fuel cell associated with reactant and generated gases and the ions path.

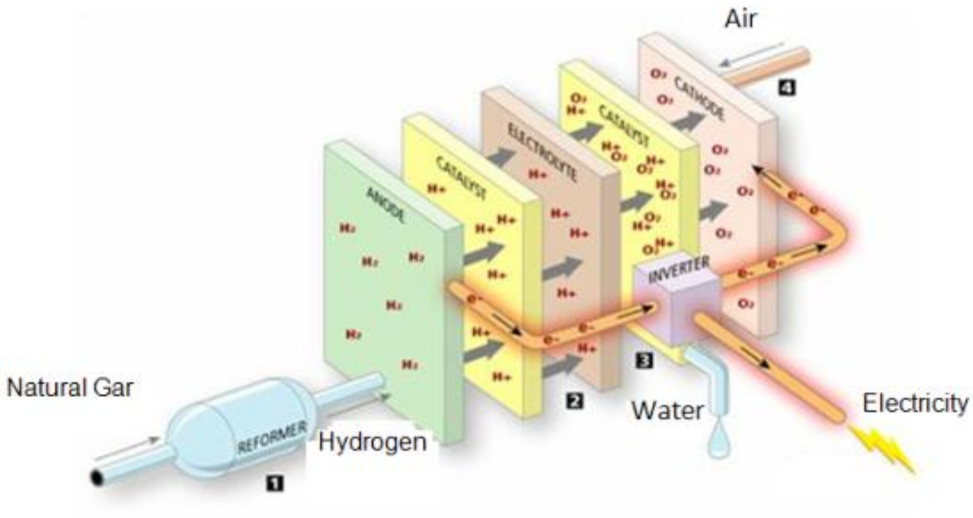

Figure 1: overall view of a fuel cell associated with reactant and generated gases and the ions path.

A fuel cell is an energy conversion device which has the capability of producing electricity until their electrodes is being supplied with oxidant and fuel. Concisely, in MFC's fuel injected to anode side and oxygen to cathode side continuously. Through performing electrochemical reaction in electrodes, the created electrical potential made an electrical current.

Theoretically, any substance which has the capability of being oxide by an oxidant is suitable to use as a fuel in anode electrode. In addition that it should be considered that materials which are used as oxidant or fuel must be able to injected continuously (like fluids) to microbial fuel cell. Similarly, oxidant is a material (fluid) which can be revived with an appropriate rate. Hydrogen could be counted as an ideal fuel in MFC's due to its high potential of reacting and large density of energy. Hydrocarbons can be converted to hydrogen through a catalytic reaction and required Oxygen in the fuel cell can be obtained from the air directly.

4. *Principle of micro biofuel cell performance*

All types of fuel cell have similar functions. In other words hydrogen (fuel) and oxygen (oxidant) are injected to anode and cathode respectively. In oxidation-reduction reaction, electrons is provided by hydrogen atom, and consumed by oxidant (oxygen). But in a fuel cell, electrons cannot directly be transferred between the half reactions. An electron is produced in an oxidation half reaction, where it is called an anode. Then, the released electron moves through a wire to reach the cathode, where it will be used in the reduction half reaction. This electron transfer produces a charge gradient between the cathode and anode. Motivated by the charge gradient, the ion exchange membrane makes the ion transfer possible. This balances the charges in the cathode and the anode. The result of this electron transfer is an electrical current, or in other words, electricity.

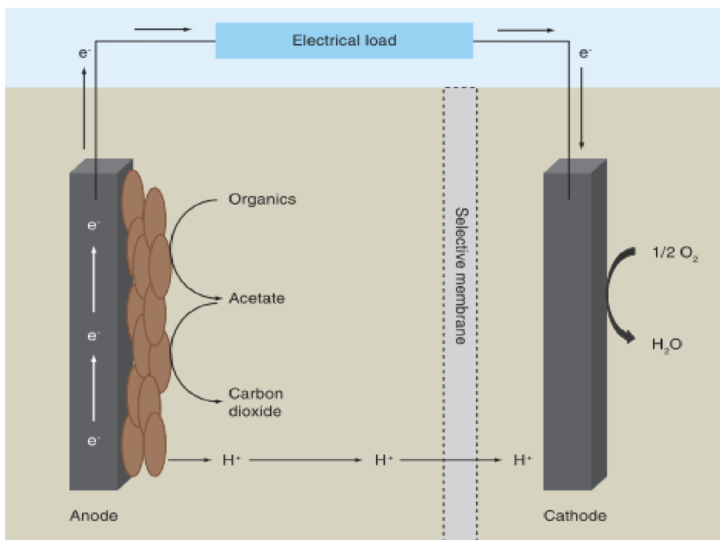

Figure 2- Schematics of an MFC with a Membrane

The Microbial Fuel Cell has been designed based on the same concept. But Main difference between MFC's and other fuel cells are in their anodes. Anode in MFC's includes Enzyme , mediator and substrate. In the chemical reaction at the anode, the fuel is oxidized by Enzyme and then generates electrons.

Consequently, it consists of four elements: anode, cathode, an ion exchange membrane, and a microbial fuel. These four parts function as follows:

4.1. *Anodic chamber*

The main purpose of anodic chamber is supplying fuel for the MFCs. through this chamber fuel reach to anode side and catalytic layer, then consumed by an electrochemical reaction. Due to prevent membrane from drying, water vapor are used to humid entering hydrogen.

4.2. *Anode*

Some bacteria work as anodes, and produce energy by oxidizing organics. Any oxidation reaction requires an electron acceptor, which in this case could be an oxygen molecule, or any other ions present in water that could be reduced. There are many different ways that bacteria can carry their electrons from the oxidation site to the electron acceptor. Some bacteria use the oxygen dissolved in water and reduce it inside their cells. A few others can actually transfer the electrons outside their bodies and donate the electrons to the oxidizing agents. These bacteria can grow in anaerobic environments, since they don't require oxygen. Oxygen is actually toxic and deadly for some of them. In a fuel cell they will donate their electrons to the anode electrode and these electrons will be used on the cathode side. This electron transfer is not only an energy source for the bacterial culture, but it can also produce energy in an external resistance between the anode and the cathode.

4.3. *Cathodic chamber*

Even if pure oxygen increases the efficiency of Fuel cell, we usually use air as an oxidant which is more economical and safer. During a catalytic electrochemical reaction between protons and oxygen, water becomes generated. Some water also moves toward the cathode through the membrane. Accumulation of liquid water in cathode causes partial or total blockage of holes in diffusion layer and prevents oxygen to reach to the catalyst sites.

4.4. *Cathode*

There are different types of cathodes, and there are different chemicals used in them. The most economical cathode would use dissolved oxygen as the electron acceptor. Concentration of the oxygen molecules is very low inside the water, so this kind of cathode will not produce a very large driving force in comparison to other types of cathodes. On the other hand, this type of cathode doesn't need replacement, since the only element it consumes is oxygen, allowing it to perform for a long period of time.

4.5. *Ion Exchange Membrane*

While the cell is performing and producing power, the charge of the cathode and anode becomes unbalanced. Bacterial culture produces protons in the solution, so the anode becomes more positive. Since the oxygen is reduced in the cathode, the cathode side becomes negative. In order to keep the charge balance in cell there has to be an ion exchange membrane between the anode and the cathode. The main difficulty is that this membrane can't be exposed to air, because the anode side has to stay anaerobic. This selective membrane only use protons move from anode side toward cathode.

5. *The Microbial Fuel*

Totally any compound that can be oxidized by microorganisms is suitable to use as fuel in MFCs. research has shown that glucose and acetate are unusually good food sources for the microbe on the anode. Glucose and acetate can be broken to sugars, carboxylic and alcohols which are consumed by microorganisms on the anode, so waste water is a good choice to use as the food for MFCs. Hence MFCs can be used in water treatment plant to reduce the organic contamination. In following table we introduce a summary of MFC components and material which are used to build MFCs.

Table 1- Basic components of microbial fuel cells

Items	Material	Remarks

Anode	Graphite, graphite flat, carbon paper, carbon-cloth, pt, pt black, reticulated vitreous carbon(RVC)	Necessary
Cathode	Graphite, graphite flat, carbon paper carbon-cloth, pt, pt black, RVC	Necessary
Anodic Chamber	Glass, polycarbonate, Plexiglas	Necessary
Cathodic Chamber	Glass, polycarbonate, Plexiglas	Optional
Proton exchange system	Proton exchange membrane: nafion ultrex, polyethylene-poly (system-co-divinylbenzene);salt bridge, pt, pt black, mno_2 , fe^{3+},polyaniline electron mediator immobilized on anode	Necessary
Electrode catalyst		Optional

6. *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 2together with their substrates.

Table 2- Microbes used in MFCs

Microbes	Substrate	Applications
Actinobacillus succinogenes	Glucose	Neutral red or thionin as electron mediator
Aeromonas hydrophila	Acetate	Mediator-less MFC
Alcaligenesfaecalis, Enterococcus gallinarum, Pseudomonas aeruginosa	Glucose	Self-mediate consortia isolated from MFC with a maximal level of 4.31 W m−2.
Clostridium beijerinckii	Starch, glucose, lactate, molasses	Fermentative bacterium
Clostridium butyricum	Starch, glucose, lactate, molasses	Fermentative bacterium
Desulfovibriodesulfuricans	Sucrose	Sulphate/sulphide as mediator
Erwiniadissolven	Glucose	Ferric chelate complex as

		mediators
Escherichia coli	Glucose sucrose	Mediators such as methylene blue needed
Geobactermetallireducens	Acetate	Mediator-less MFC
Geobactersulfurreducens	Acetate	Mediator-less MFC
Gluconobacteroxydans	Glucose	Mediator (HNQ, resazurin or thionine) needed
Klebsiellapneumoniae	Glucose	HNQ as mediator biomineralized manganese as electron acceptor
Lactobacillus plantarum	Glucose	Ferric chelate complex as mediators
Proteus mirabilis	Glucose	Thionin as mediator
Pseudomonas aeruginosa	Glucose	Pyocyanin and phenazine-1-carboxamide as mediator
Rhodoferaxferrireducens	Glucose, xylose sucrose, maltose	Mediator-less MFC
Shewanellaoneidensis	Lactate	Anthraquinone-2,6-disulfonate (AQDS) as mediator
Shewanellaputrefaciens	Lactate, pyruvate, acetate, glucose	Mediator-less MFC but incorporating an electron mediator like Mn (IV) or NR into the anode enhanced the electricity production
Streptococcus lactis	Glucose	Ferric chelate complex as mediators

7. Design of microbial fuel cell (MFC)

Based on physical shape MFCs calcified in different groups as bellow:

7.1. *Two-compartment MFC systems*

Two-compartment MFC systems are frequently work in batch mode often with a chemically defined medium to generate energy. They are already used only in laboratories. This type of MFCs has an anodic and cathodic champers connected together by PEM. Mediates proton transfer from cathode to anode while blocking diffusion of oxygen into anode. This type of MFC

used for waste treatment with power generation. The components can be variant shapes. The schematic diagrams of five two-compartment MFCs are shown in Figure 3.

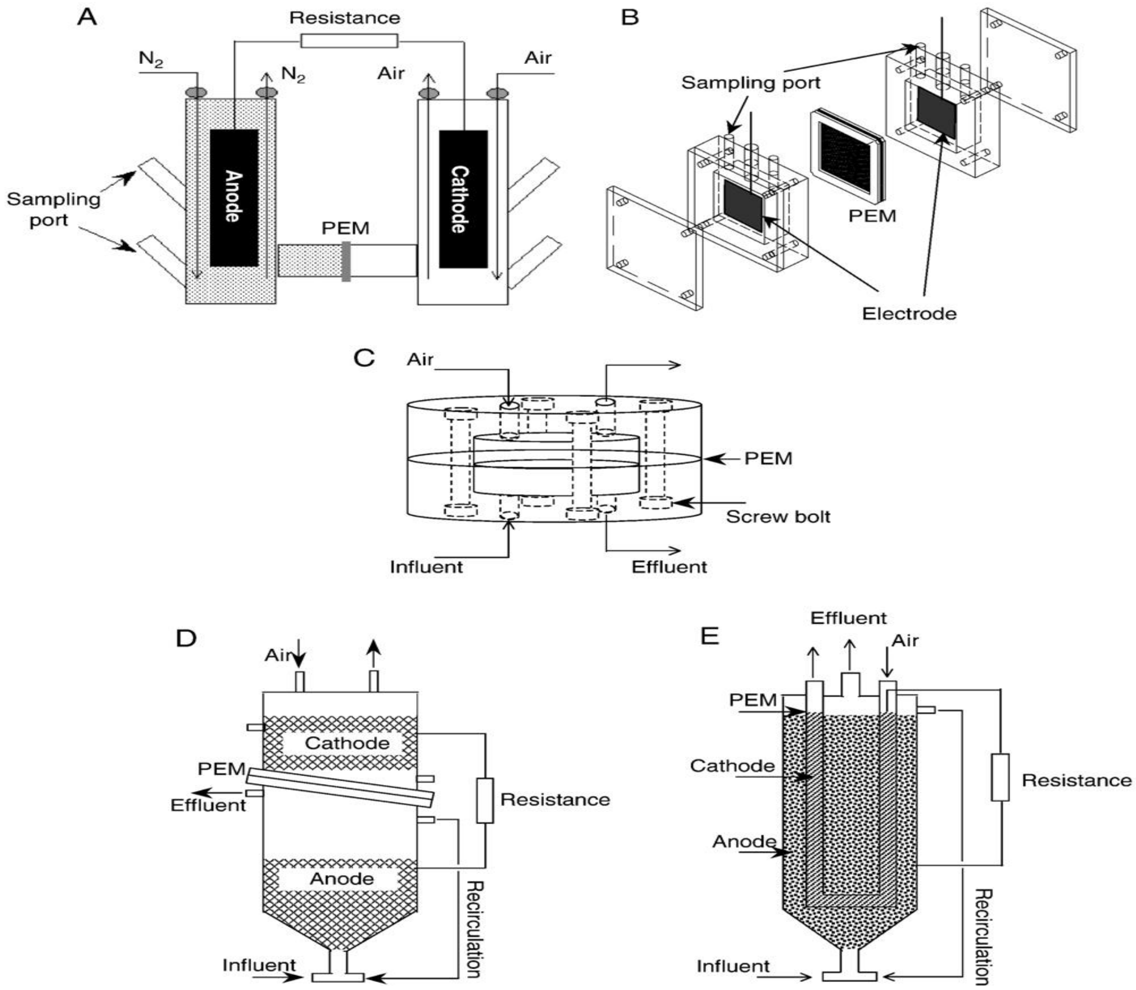

Figure.3. Schematics of a two-compartment MFC in cylindrical shape (A), rectangular shape (B), miniature shape (C), up flow configuration with cylindrical shape (D), cylindrical shape with an U-shaped cathodic compartment (E).

7.2. *Single-compartment MFC systems*

Two-component MFCs are difficult to scale up because design them are complex. Single-compartment MFCs have simple and low cost designs than two-compartment MFCs, therefore this kind of MFCs have flexible application in wastewater treatment and power generation. Usually they have only anodic chamber without aeration in cathodic chamber.

Park and Zeikus 2003 designs single-compartment MFC formed anode in anode's rectangular chamber with porous air-cathode that is directly in open air. (Is shown Fig 4A).Protons are transferred from the anolyte solution to the porous air-cathode[2].

Liu and Logan (2004) designed MFCs organized anode placed cylindrical plastic chamber and cathode is exteriority. Fig B6 is shown general view of laboratory model of bioreactor MFC. The anode was made from carbon sheet without wet proofing. The cathode was either a carbon electrode/PEM assembly fabricated by bonding the PEM directly into a flexible carbon-cloth electrode, or a standalone rigid carbon paper without PEM [3,4,5].SC-MFC consisted of a single cylindrical Plexiglas chamber with eight graphite rods (anode) in a concentric arrangement surrounding a single cathode as shown in Fig 5[6].

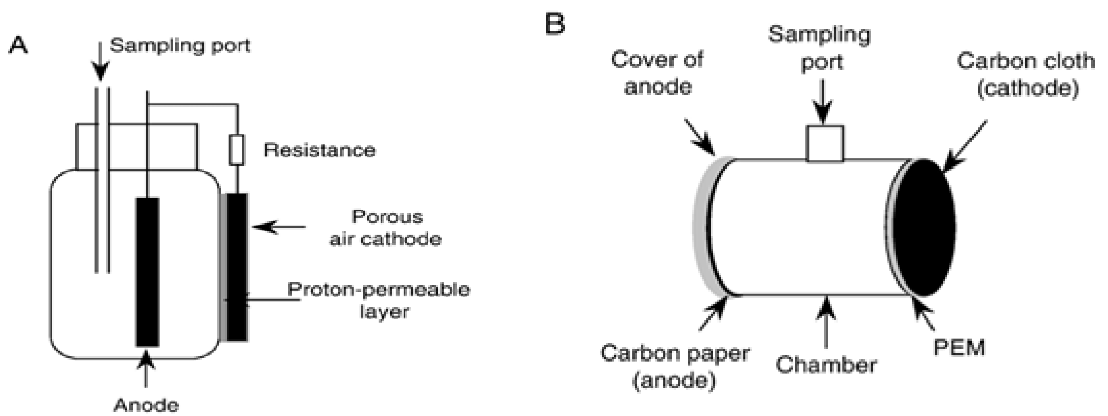

Figure 4. An MFC with a proton permeable layer coating the inside of the window-mounted cathode (A), an MFC consisting of an anode andcathode placed on opposite side in a plastic cylindrical chamber (B).

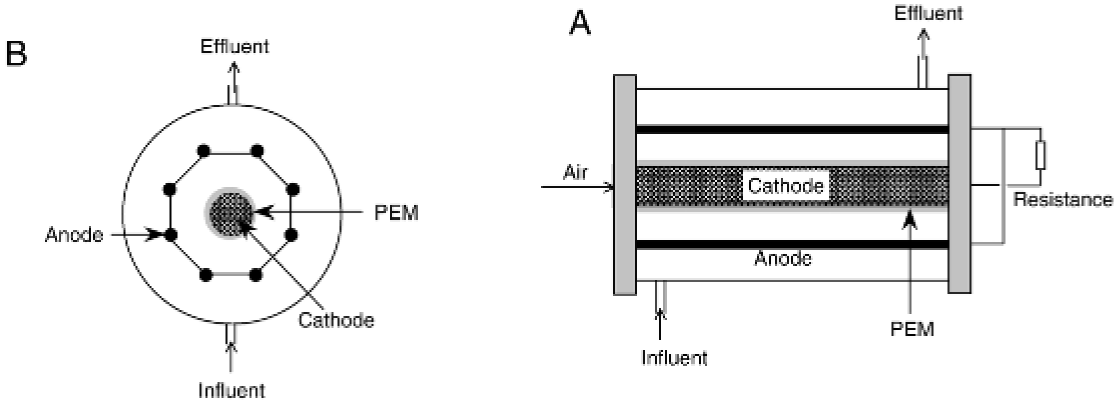

Figure 5. Schematics of a cylindrical SC-MFC containing eight graphite rods as an anode in a concentric arrangement surrounding a single cathode.

7.3. *Up-flow mode MFC systems*

Jang et al. 2004 offering another type of MFCs that had working in continuous flow (Fig 6A).This kind of MFCs Including a Plexiglas cylinder that separate two sections by glass wool and glass bead layers. This two section worked as anodic and cathodic chamber (as shown in Fig 6A). Fig 6B shows on other kind of Up-flow MFCs that is covered with disk-shaped graphite of anode and cathode in bottom and up of reactor. This mode of MFCs design inspired of general idea as shown in Fig 6B, but with a rectangular container and without a physical separation achieved by using glass wool and glass beads [7]. This mode of MFCs has not separate section between the anode and cathode. And diffusion barriers between anode and cathode supplied suitable DO for accomplishment MFCs operation.

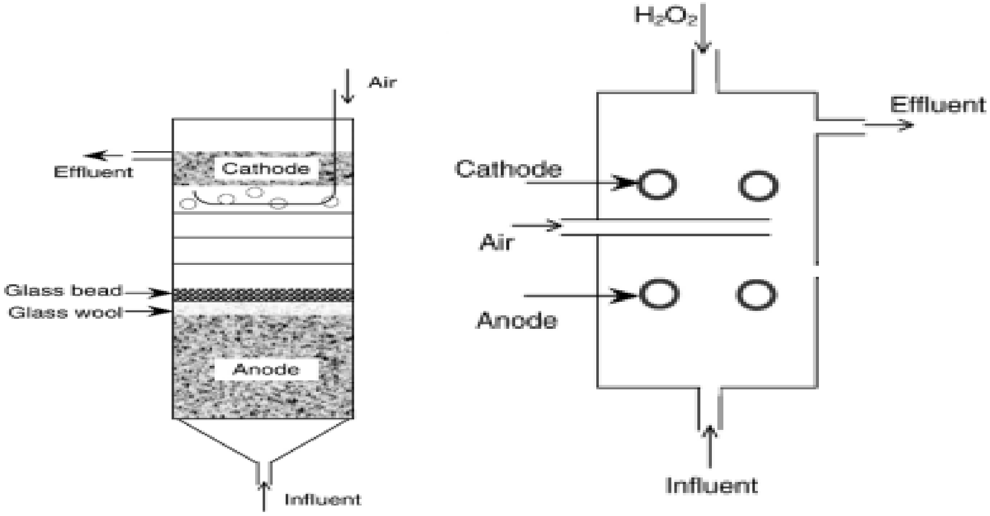

Figure 6. Schematics of mediator and membrane-less MFC with cylindrical shape (A), and with rectangular shape (B).

7.4. *Stacked microbial fuel cell*

Stacked MFC had shown in Fig 7, that for research the performance of several MFCs, connection together as series and parallel. Overvoltage several MFCs can be obtained with series and parallel connection. No obvious adverse effect in the maximum power output per MFC unit observed. Coulombic efficiencies differed greatly in the two arrangements with the parallel connection giving about efficiency six times higher when both the series were operated at the same volumetric flow rate[8]. The parallel-connected stacks have more short circuit current than series-connected stanks.This means that according to maximize Chemical Oxygen Demand (COD), if MFC units are not working independently, parallel connection has preferred.

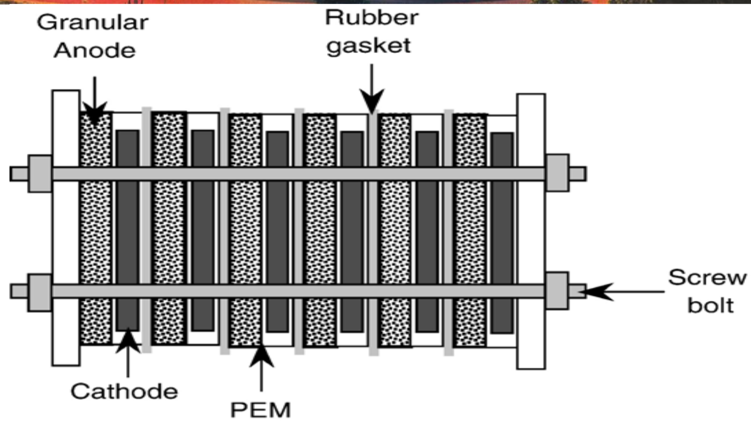

Figure.7. Stacked MFCs consisting of six individual units with granular graphite anode.

8. *Application:*

8.1. *Electricity generation*

Currently MFC is considered as clean and efficient method of generation energy. Where greenhouse gases are respected, are used in hydrogen production and electricity generation in sewage plants that feed them a series of algae or aquatic plants. Also, these methods can be used in the production ethanol from stems and leaves of corn remaining in farm. About 90% stems and leaves of corn are not used in farms that contain 70% cellulose and complex carbohydrates. Steam explosion caused due to process sugars and other compounds to waste corn can be used as feed of microbial fuel cell. MFCs do not follow the Carnot cycle because the chemical energy from fuel molecules to oxide directly is converted into electricity instead of heat. MFC theoretical efficiency is over 70% however still generating electricity from MFC very little. One of practical ways to solve this problem is that store in the device rechargeable power. MFCs suitable method for provide energy the telemetry systems that have low energy consumption, such as wireless sensors used for power generation for signal transmission in remote locations. MFCs also can be used as local power distribution systems in less developed places of the world [11].

8.2. *Wastewater treatment*

MFCs were applied onward of 1991 in the Wastewater Treatment. Urban wastewater contains many organic compounds that can be used as fuel in MFCs. MFCs with specific microbes, have special ability to remove sulfide in wastewater treatment. Sanitary waste, Swine waste water, stem and leaves of corn are waste water treatment process feeds. MFCs are contain large coral layers, therefore active microbes in their bio-electro-chemical in this two process reduce energy demand, also reduce raw sewage by anaerobic organisms. MFCs series connection can be taken better efficiency. And the remaining water in water treatment can be used in electricity system generation [8].

8.3. *Biohydrogen*

Usability of MFC is very much such as the new method of converting organic materials into hydrogen fuel. This method is done by use of bacteria in a cell electrolysis microbe with acetic acid in vinegar, where anode is graphite granules and cathode is carbon platinum catalyst.

Research teams from the University of Southern California have begun research to build fuel cells (palm size) with the driving force powering the bacteria to set up with a miniature spy planes (Insect size). But so far these demands failed due to lack of appropriate intensive energy source [12].

The team intends to determine transfer electrons in optimal conditions, to the anode surface in different conditions. In low oxygen environments of bacteria to sewanell used the metal instead oxygen for full metabolism food. That organism is able to convert electrons into the solid metal oxides directly, that it can be used in fuel cell.

Sensor:

Biosensors device is converted biological response to an electrical signal. Biosensors are used to identify specific molecules in Geology Applied Sciences potentially sensitive to recent events in Laboratory systems [13].

Such as:

1: sugar control in diabetic patients

2: detecting pesticides and water contaminants

3: Drug discovery and evaluation of new drug compounds, biological activity

An important part of applications biosensors in chemical reactor converters in order to:

1: Measure the heat generated (absorbed) by the reaction (biosensors calorimetric)

2: Measure the motion of electrons produced in the oxidation and reduction reaction (Ammete biosensor)

3: Measure the effects of mass reactant or product (electrical biosensors)

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