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Research Article

Optimizing the Metabolic Energy Gains to enhance the performance of a Microbial Fuel Cell (M.F.C)

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Abstract

A Microbial Fuel Cell is a device that can be used to exploit the bio-electrochemical interactions between the bacteria and the organic matter present in the substrate to produce electricity. For doing so, the bacteria oxidize the organic matter and deposit the electrons at a suitable electrode. Despite the promising nature of the M.F.C, this device falls short of commercialization due to its low power density. This paper presents a new idea, which theoretically resolves the energy problems associated with a M.F.C by optimizing the factors which affect the energy production the most; viz thermodynamic properties (Entropy, Enthalpy), bacterial competitions, variations in cell potential with rising temperatures and electrode selection.

Keywords: *Bacterial Competition, Cell potential, Electrode potential, Entropy.*

1. Introduction

In this energy deficient era, it has become necessary to exploit every possible potential energy source. "*Energy from waste*" had been a dream until the early 90's, when the Microbial Fuel Cell paved the way for researchers to exploit the bio-electrochemical interactions of bacteria to cogenerate electricity along with waste water treatment. A Microbial Fuel Cell is an ingenious device which replicates the respiratory pathway, utilized by bacteria to meet their energy demands, in anaerobic conditions. The bacteria oxidize the organic matter present in the substrate to produce electrons, protons and carbon-di-oxide. These electrons are transferred to the anodic electrode by the bacteria (mediator less) or by an external catalyst (mediator) like neutral red or toluylene red. From the anodic electrode, these electrons pass through an external circuit which is connected to the cathodic electrode. The flow of electrons produces electricity, which can be used for other purposes. Apart from converting the chemical energy stored in the substrate to electrical energy, a M.F.C also reduces the Chemical Oxygen Demand (COD) of the substrate by a notable 50% (Cheng et al., 2006). Many experiments, involving the MFC, have been conducted to test their electricity generation capabilities and waste water treatment applications. A maximum of 3500 mW/m^2 of power density and a COD removal of 70% has been recorded till date.

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1.1 Overview of a M.F.C

Microbial Fuel Cells can be classified into various sub-categories which primarily depend on the design of the cell and other factors including the type of substrate used in the anodic compartment, mediator and mediator less M.F.C's etc. The most common kind is a dual compartment cation specific membrane type M.F.C.

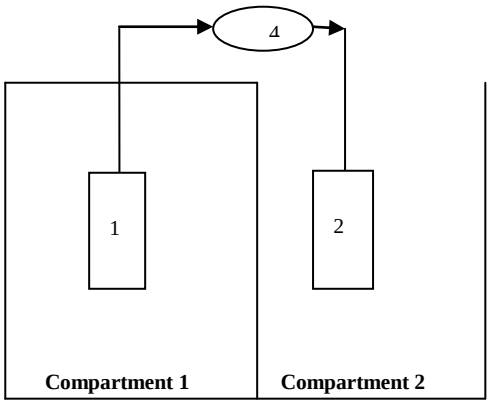

Fig.1 Typical Microbial Fuel Cell

This cell has a very simple exo-skeletal design which includes two compartments: 1) Anode 2) Cathode respectively. These compartments are separated by a Cation Specific Membrane (CSM) which allows only the protons to pass through to the other side. The anodic compartment uses the waste water (rich in organic

substrate) as an electrolyte; the bacteria oxidize these organic materials present in the waste water to produce protons, electrons and carbon-di-oxide. The protons pass through the CSM and enter the other compartment (Cathode) and combine with oxygen and electrons to form water. The anodic compartment is sealed from the environmental conditions to preserve an anaerobic atmosphere.

The following figure represents a typical Microbial Fuel Cell in its very basic form.

Fig.1. represents a typical M.F.C in its simplest form, as shown; it consists of the following parts
1:- Anodic Electrode (Carbon, for lab purposes)
2:- Cathodic Electrode (Graphite, for lab purposes)
3:- Cation Specific Membrane
4:- Multimeter
Compartment 1:- Anodic Compartment
Compartment 2:- Cathodic Compartment

1.2 A Bacterial Perspective

Apart from having the right nutrients and substrate, bacteria need a suitable electron acceptor to grow and multiply. Based on the electron accepting phenomena, bacteria gain energy in two broad pathways; viz Respiration and Fermentation. A brief idea about these two pathways is given below;

1.3 Respiratory Pathway

Microorganisms multiply and grow by utilizing the energy they gain during the electron transfer. In this pathway, bacteria liberate electrons from an electron rich substrate at low redox potential and transfer it to a suitable electron acceptor at a high redox potential via various complex electron transfer mechanisms. The bacteria do not use the energy produced by the flow of electrons directly, instead, they utilize the potential difference created between the inside of the cell membrane and the electron acceptor to regenerate the ATP (Adenosine tri phosphate) molecules. Hence, greater the potential difference between the electron acceptor and donor, the greater will be the energy gained by the bacteria/microorganisms to reproduce and survive the bacterial competitions.

1.4 Fermentation Pathway

This metabolic pathway is utilized by microorganisms when a suitable electron acceptor is not available. It follows the same mechanism as the respiratory pathway, but with the substrate as both the donor and acceptor of electrons. This pathway has its own pros and cons; this metabolic pathway can be used to degrade polymers in environments where respiratory organisms are of no use.

2. Bacterial Metabolism in a M.F.C

In a M.F.C, the anodic compartment is engineered with such precision that, the bacterias follow the respiratory pathway in an anaerobic environment. The M.F.C is a Bioelectrochemical System (BES) where the electron acceptor happens to be an electrode. The need for energy which is endorsed by the high potential difference between the substrate and the electron acceptor is the incentive for the BES. The bacteria transfer the electrons to the electrode (electron acceptor) and regenerate energy carrying molecules (ATP) to sustain their existence. The result, is a process in which bacteria serve as a biocatalyst to transform an electron rich substrate i) into electrons, which are transferred to the electrode, ii) into protons which migrate to the cathode and iii) into oxidized products which leave the reactor. The electrons flow through an external electrical circuit towards the cathode

3. Plausible idea for enhancing the power density

The maximum power density that was recorded and published was 3200mW/m^2; this power density can be increased by a notable amount if the metabolic energies gained by the bacteria are high. The metabolic energies are responsible for the bacterial growth and multiplication. Hence, the production of electrons is indirectly dependent on the energy that the bacteria gains during its metabolic pathway.

3.1 The Gibbs Energy

The metabolic energy gained by the bacteria can be attributed in terms of change in Gibbs free energy (ΔG). Gibbs free energy, in its very basic form, can be considered as the amount of energy available to do work. Initially, the energy possessed by the bacteria can be considered as G_1 and after the bacteria gains energy through the metabolic pathway, its energy can be considered as G_2. Now, the effective energy that the bacteria can utilize to multiply and sustain life is given by G_2-G_1 (ΔG). This Gibbs energy is a function of Enthalpy (H), Temperature (T) and Entropy (S). The equation relating these three thermodynamic properties is given by

$$G = H - TS \quad (1)$$

The above equation implies that, the *Gibbs energy increases with decrease in Entropy*.

3.3 Equations pertaining to Gibbs Energy and Entropy

The following equations provide a relation between the Gibbs energy (G), Entropy (S), Temperature (T) and cell potential (E_c) respectively;
Considering a closed anodic system, then;

$$d(U) = d(Q) + d(W) \quad (2)$$
(From the first law of thermodynamics)
$$d(U) = d(Qrev) + d(Wrev) \quad (3)$$
(For a particular reversible process)
$$d(Qrev) = Td(S)$$

$$d(Wrev) = -Pd(V)$$

Substituting the last two equations in (2) we have,

$$d(U) = -Pd(V) + Td(S) \quad (4)$$

The equation relating Enthalpy (H) to the Internal energy (U), Pressure (P) and Volume (V) is given by

$$d(H) = d(U) + Pd(V) + Vd(P) \quad (5)$$

Differentiating equation (1), we get

$$d(G) = d(H) - Td(S) - Sd(T) \quad (6)$$

Substituting (5) in (6), we have

$$d(G) = d(U) + Pd(V) + Vd(P) - Td(S) - Sd(T) \quad (7)$$

Substituting (4) in (8), we have

$$d(G) = -Pd(V) + Td(S) + Pd(V) + Vd(P) - Td(S) - Sd(T) \quad (8)$$

$$d(G) = Vd(P) - Sd(T) \quad (9)$$

(9) Can be interpreted in the following way

$$\partial G/\partial T = -S \text{ [constant pressure]} \quad (10)$$

From Electrochemistry, we have a relation between Gibbs energy, number of moles of electron (n), Faraday (F) and Cell potential (E_c) given by

$$G = -nFE_c \quad (11)$$

Substituting (12) in (11)

$$\partial(-nFEc)/\partial(T) = -S \quad (12)$$

$$nF\,\partial Ec/\partial T = -S \quad (13)$$

3.3 Bacterial Competition

The bacteria responsible for liberating electrons from the substrate have to face competitions from other microorganisms for the survival of their domain. For doing so, the bacteria spend a considerable portion of their energy which is conducive to the loss in overall Gibbs energy associated with the bacteria. As mentioned earlier, the loss in Gibbs energy accounts to the reduced efficiencies of electron liberation.

Bacterial Competitions can be reduced by a notable amount if we inoculate the anodic compartment with the electricity liberating bacteria. This gives them (bacteria) an upper hand and helps them focus their energy towards electron liberation

3.4 Role of Entropy

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The equations (9), (10) show the perpetual dependence of Gibbs energy on Entropy. Hence, it can be safely concluded that, the Gibbs energy increases with decrease in Entropy (from (1), (9), (10)). (11) Represents the correlation between Gibbs energy, Faraday (F) and Cell potential (E_c). This correlation when substituted in (10) tells that, the Entropy of the system is proportional to the change in Cell potential with changing temperatures ($\partial(E_c)/\partial(T)$). As a result, if the system's (M.F.C) temperature is kept constant throughout the experiment, then the Entropy of the system can be controlled to an appreciable extent and is conducive to increasing the electron flow.

3.5 Redox Potential Difference

As mentioned in (1.3) the metabolic energy gained by the microorganism is increased if the redox potential difference between the electron rich donor and the acceptor is high. In a BES, the electron acceptor is an electrode. This means that, having a good electro negative substance as an electrode will increase the change in Gibbs energy and will eventually increase the electron transfer. Substances like Platinum (Pt), Gold (Au), Cobalt (Co) etc can be used as a coating on the Carbon electrode to enhance the electron transfer rate.

Conclusions

With increasing need for alternate and sustainable energy, the demand for waste to energy is at its zenith. M.F.C's are excellent tools which cater to this need. A M.F.C utilizes the Bioelectrochemical method to convert the chemical energy stored in the substrate into electrical energy. One major reason for the unpopularity of M.F.C's among the commercial industries is its low power density. Hence, it is necessary to provide a solution to this punctuating factor and provide an incentive to the industries to invest in the R&D of this ingenious "Waste Treatment cum Power source". The theoretical improvement for power density, provided in this paper, revolves around the Thermodynamic factors which affect the metabolic energy gained by the microorganisms. A more detailed practical work of this paper is necessary to establish any remarkable outcomes in this field.

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