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Bioelectrochemical Devices for Energy Production

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Abstract. The development of fuel cells device, which used bioelements as catalyst, converts the chemical energy from a fuel into electricity through an electrochemical reaction with oxygen oxidizing agent, and demonstrates the potential of electrochemical techniques for energy generation. The development of sustainable energy production prompted the researcher community to propose and investigate the use of biocatalysts. This article review presents the development of bio catalyst in biofuel cell devices. Two kinds of biocatalyst are used to produce electricity: enzyme and microorganisms. Enzymatic biofuel cell and microbial fuel cell are presented after an historical review for each device. Effect of material electrode and design of the electrode are discussed to improve the electrical connection of biocatalyst (enzyme or microorganism) and thus to enhance the energy production.

Keywords: Bioelectrochemistry, enzymatic biofuel cell, enzyme immobilization, microbial fuel cell, yeast.

1 Introduction

The rising concerns related to energy availability and independence, and the negative environmental impact of using fossil fuels make it important to develop new energy sources that are plentiful, renewable and environmentally friendly.

The fuel cells convert the chemical energy from a fuel (hydrogen or methanol) into electricity through a chemical reaction with oxygen oxidizing agent (mainly oxygen). These systems demonstrate the potential of electrochemical techniques for energy generation. However, catalysts such as noble metals (ie: platinum, palladium ...) are necessary to activate the reactions on the electrode. The development of sustainable energy production prompted the researcher community to propose and investigate the use of biocatalysts as an alternative to minerals [1]: the biofuel cells. Currently two kinds of biofuel cells exist : i) enzymatic biofuel cells, in which the catalyst is carried out by some enzymes and ii) microbial biofuel cell (MCF) in which micro-organisms

(i.e. bacteria or yeasts or a community of micro-organisms) are used to catalyze the electrochemical reactions.

In all cases, biocatalysts must be associated to the electrode to allow the electrical connection. The electrodes become thus the contactors which promote the contact between solid material and biocatalyst. According the biocatalyst configuration, it can be in solution or fixed on the electrode.

2 Enzymatic biofuel cell

The use of non-renewable energy sources is now a necessity because of the increase of energy consumption and its environmental impact. An alternative method for energy production must be found to reduce the combustion of fossil fuel. In this context, a fuel cell based on hydrogen as carburant and oxygen as oxidant can generate power through the electrochemical conversion of fuels directly into electricity. The absence of combustion is an extremely attractive option from an environmental standpoint. The reaction of the fuel is governed by electrochemical oxidation and generates electrons at the electrodes and consequently a voltage. This reaction is associated to the production of water and heat. The performance of the fuel cell (battery) depends largely on the value of the voltage, which can be decreased by the use of catalysts.

Enzymatic Biofuel cells use biocatalysts (enzymes), to convert chemical energy into electrical energy with a low power output at room temperature and under physiological conditions (figure 1).

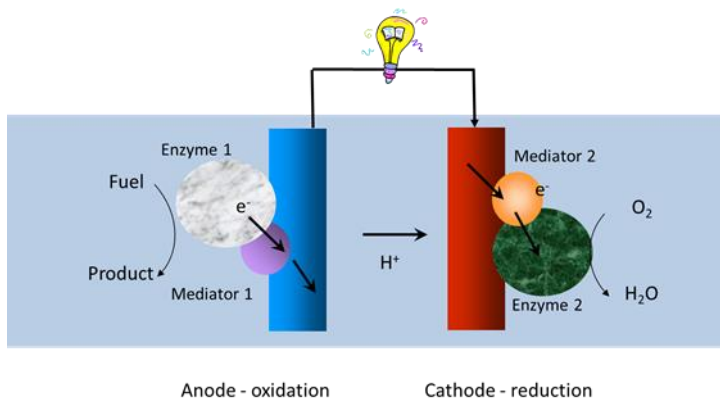


Fig. 1. : Schematic configuration of biofuel cells that use biocatalysts as enzymes to convert chemical energy into electrical energy

The advantage of an enzymatic biofuel cell is to exploit the enzyme selectivity. In the case of use of Glucose oxidase enzyme, separation of anode and cathode by mem-

brane is necessary to avoid diffusion of oxygen to the anode. An original approach based on the configuration of the electrode can allow elimination of membrane. Both electrodes can be immersed in one compartment containing the fuel and the oxidant concurrently. Hence, miniaturization can be achieved (down to micrometer scale) for various applications (e.g., for implantable devices, micro devices or for autonomous systems of quality control in food environment) [2].

3 Microbial fuel cell:

However, the two major problems in enzyme-based systems are:

- i) the short lifetime of the enzyme due to the reduction of stability in functioning
- ii) the low power densities caused by a low electron transfer rate from the enzyme active site to the electrode [3].

The first problem can be solved by using microorganisms which maintain the integrity and environment for enzymatic reaction.

3.1 Compost microbial fuel cell

Microbial fuel cells use the available substrates from renewable sources and convert them into products with simultaneous production of electricity [4]. The natural potential gradient between the sediment and upper toxic water can be used to generate electrons thank to the microbial oxidation of organic matter flow from the anode [5]. Electrons are then released in external circuit to go to the cathode. Although the power output from these MFCs is moderate, such levels of output are considered to be sufficient to serve as remote power sources in aquatic environments in nomad systems [6,7].

Surface electrode modification

The formation of electroactive biofilm onto the electrode surface is the key factor for the efficiency of MFC. In the case of inoculum resulting of mixture of bacteria species (for instance if compost are used) the interaction between biofilm and electrode is essential to ensure the electronic connection. Graphene modified electrode by layer-by-layer method has been investigated [9].

Evolution of the current density in function of time of the MBC with a resistance of $1\text{k}\Omega$ is reported in Fig. 2. After 18 days, the SSF electrode was enabled to produce any current contrary to the SSF/(PEI/rGO)5 which showed a current of 110 mA/m^2 . This could mean that the biofilm, adhered to a modified surface of rGO, presents a better connection to the electrode than with only stainless steel. At a time of 30 days, the power output obtained was 8.19 mW/m^2 for the SSF/(PEI/rGO)5 electrode whereas no power output was observed for the SSF alone.

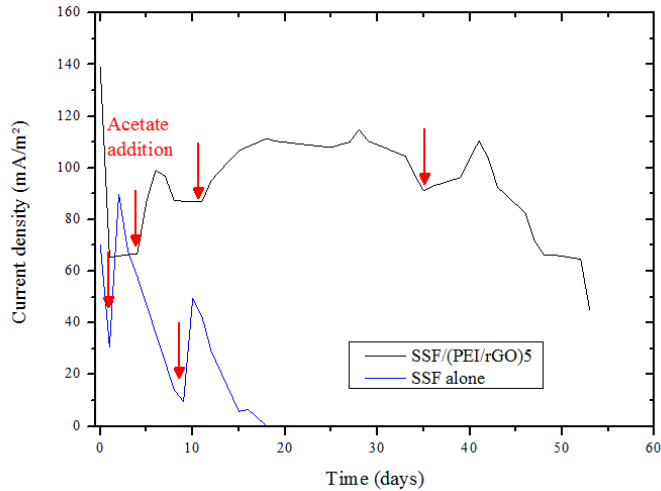


Fig. 2. Debit of the electrode with a resistance of $1\text{ k}\Omega$ between the working electrode (either SSF/(PEI/rGO)5 or SSF). The addition of acetate is reported through the red arrows (from [87]).

Electropolymerization of conducting polymer as pyrrole has been used to modify the electrode and improve the electronic conduction, and therefore increase the power density of the cell [10].

Air cathode electrode

Single chamber microbial fuel cell (SCMFC), an evolution of MFC system offers many advantages such as simple, sustainable and almost no pollutant potential released. The SCMFC system involves air-breathing cathode which is designed to expose to the free air to allow its direct contact with oxygen as terminal electron acceptor.

Air-breathing cathodes use gaseous oxygen as readily accessible, inexhaustible, sustainable, and eco-friendly terminal electron acceptor [11]. Oxygen in the free air has a higher concentration than in its dissolved-form due to its poor solubility and small diffusion coefficient in aqueous solution which limited the cathodic reaction. Moreover aqueous phase cathode systems obligatory need continuous aeration which is energy consuming contrary to air-breathing cathode.

Carbon felt (CF) has been modified by integrating conductive polymer polypyrrole (PPy) and platinum nanoparticles to yield an effective air-breathing cathode. Modification of CF was conducted by in situ electrochemistry in two steps.

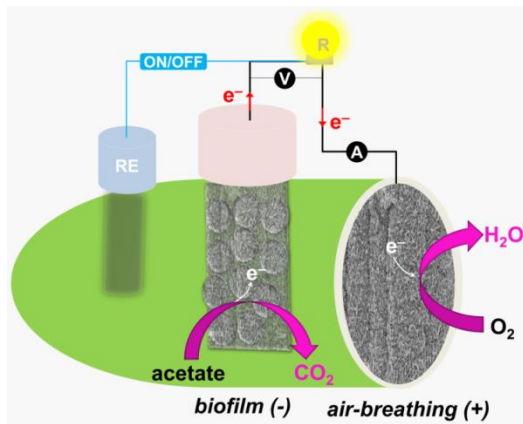


Fig. 3. Designed system for fuel cell testing and scrutinizing.

3.2 Yeast fuel cell

Yeasts are also a good candidate for a biological fuel cell. Baker's yeast, *Saccharomyces cerevisiae*, can be used without sterilization procedures or maintenance of live cultures or labile enzymes. Yeasts grow rapidly under both aerobic and anaerobic conditions, have simple nutritional requirements, and can utilize a large variety of substrates [12].

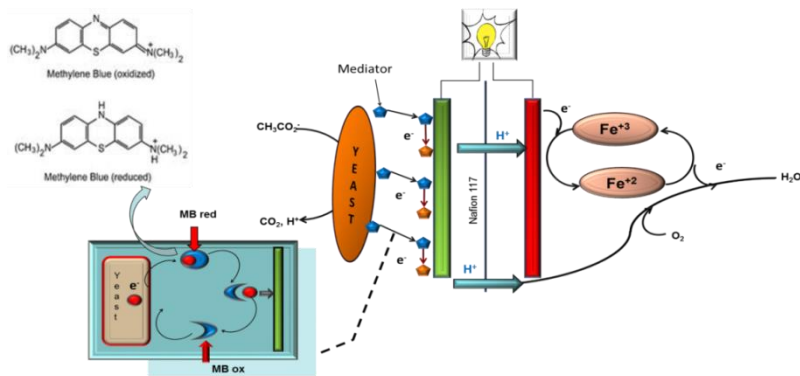


Fig. 4. Schematic of yeast fuel cell system

A two compartment fuel cell is used with two electrodes separated by a proton conducting membrane. The reduced mediator transfers the captured electrons to an electrode, producing an electric current and re-oxidizing the methylene blue as shown in fig 4. Neutral Red (NR), another redox dyeing, is a proper redox molecule, can be

used in MFCs. This compound has been immobilized by electropolymerization process and used as redox mediator molecule directly at the electrode. Indeed, the electropolymerization of NR will form a NR polymeric film acting thus as a network including many electrons carriers that will further prevent the mediator from leaching upon MFCs utilization cycles [13].

4 Conclusion

This article showed the recent applications of biocatalyst to produce electricity with specific device called biofuel cell. Enzymes or microorganisms can be used to catalyze oxidation reaction and transfer electron to the electrode. Effect of electrode modification and its design as like air cathode electrode have been described.

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