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Working Principle and Application of Microbial Fuel Cell

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Abstract

Microbial fuel cell (MFC) is a device that uses microorganisms to convert chemical energy from organic matter directly into electrical energy. It is considered to have the potential for a wide range of applications to meet future human energy needs fuel diversity. This paper introduces the basic working principle of MFC and illustrates the electrode material, membrane and cell configuration selection on the performance influence of MFC. In addition, the application progress of MFC in recent years is reviewed, including sewage treatment, microbial electrolysis cell (MEC) and microbial desalination cell (MDC). Finally, the development direction of MFC is prospected: membrane and electrode materials need to be further studied, and MFC coupling technology needs to be continuously promoted.

Keywords: microbial fuel cell, wastewater treatment, microbial electrolysis cell, microbial desalination cell

1. Introduction

As water pollution becomes increasingly serious, it is urgent to develop efficient, environmentally friendly and low-cost water treatment technology. Microbial fuel cells (MFC) can use microorganisms as catalysts to degrade pollutants in water, while realizing the function of power output and waste recycling, which has attracted the attention of many researchers. Besides, to compensate for some of the limitations of MFC (e.g. low energy density and high energy losses), other new technologies have been derived, such as microbial electrolysis cell (MEC) and microbial desalination cell (MDC). This paper describes the working principle of MFC, analyzes the factors that affect the performance of MFC, introduces the practical applications in recent years, and ultimately prospects the future development of MFC based on the existing shortcomings.

2. Working Principle

The classic double-chamber structure of the MFC consists of an anode chamber, an ion exchange membrane, and a cathode chamber (Figure 1a). The principle of electron production is that electroactive microorganisms (EAM) produce electrons and protons by metabolizing the anode substrate. Due to the potential difference between the cathode and the anode, the anode electrons pass through the external circuit to the cathode and supply electron acceptors in the cathode region (Zheng & et al., 2021). The protons migrate through the membrane to the cathode region, combine with the electron acceptors and accept electrons to produce water, thus forming a circuit and generating electricity (Zheng & et al., 2021). Using acetate as the substrate, the electrode reaction is as follows:

Anode reaction:

$$CH_3COO^- + 2H_2O \rightarrow 2CO_2 + 7H^+ + 8e^-$$

Cathode reaction:

$$O_2 + 4e^- + 4H^+ \rightarrow 2H_2O$$

MFC components have different influences on battery performance, mainly in cell configuration, electrode material and exchange membrane selection.

2.1 MFC Configuration

The MFCs that are commonly studied are mainly divided into two categories: single-chamber and double-chamber, which are similar in principles, but each has its own advantages and disadvantages. MFC was firstly a double-chamber structure, which is easy to study the anode, ion exchange membrane and cathode separately, and the cathode and anode chambers can pass into independent electrolytes. The membrane's main function is to transfer protons and block oxygen from the cathode chamber to the anode. The commonly used exchange membranes are cation exchange membranes and proton exchange membranes, but they are generally expensive and unsuitable for large-scale applications (Zhai & et al., 2016).

The single-chamber MFC is widely in use at present, where the cathode and anode are in the same reaction chamber, and the cathode is directly exposed to the air (Figure 1b). No external aeration is required, and the cathode directly uses the oxygen in the air as an electron acceptor to generate water (Wang et al., 2014). It has a good development prospect without secondary pollution and negligible internal resistance. Research shows that the power density of single-chamber MFC can reach 262mW per square meter, much higher than that of two-chamber MFC under the same conditions (Sun, 2009).

2.2 Electrode Material

The anode is directly involved in the oxidation reaction catalyzed by microorganisms, so the use of high-performance cathode materials is essential. Excellent anode materials should have low resistance, corrosion resistance, high porosity and high specific surface area, so the materials commonly used in research are carbon paper, carbon cloth, graphite rods, carbon foam, stainless steel mesh and graphite fiber brushes (Wang, Park, & Ren, 2015). The cathode usually uses graphite, carbon cloth or carbon paper as the basic material, but it is not effective directly and needs to be improved by attaching a highly active catalyst to accelerate the reaction rate (Sun, 2009). The current research on MFC mainly focuses on non-platinum catalysts. For example, the study by Lin et al. (2018) shows that when Fe $(PO_3)_3$ /FeP /PGC was used as the cathode catalyst, the maximum power output of MFC was about 1.162 W/m^2, which was greater than that of platinum (1.052 W/m^2) as the control. Platinum is expensive, so this kind of research can reduce the cost of MFC and expand the practical application.

2.3 Membrane Material

The exchange membrane of the MFC is a critical component to maintain the pH balance of the reaction solution for efficient proton or ion transport and to inhibit the permeation of the reaction gas to the anode. Nafion membrane is currently the most studied, a per-fluorinated acid proton exchange membrane with high ionic conductivity (10^{-2} cm S^{-1}) (Sun, 2009). Logan and Oh (2006) illustrated that when the area of the exchange membrane is smaller than the electrode membrane, the internal resistance increases and the output power decreases. Kim et al. (2007) found that the output power of an anion exchange membrane is higher than that of a proton exchange membrane.

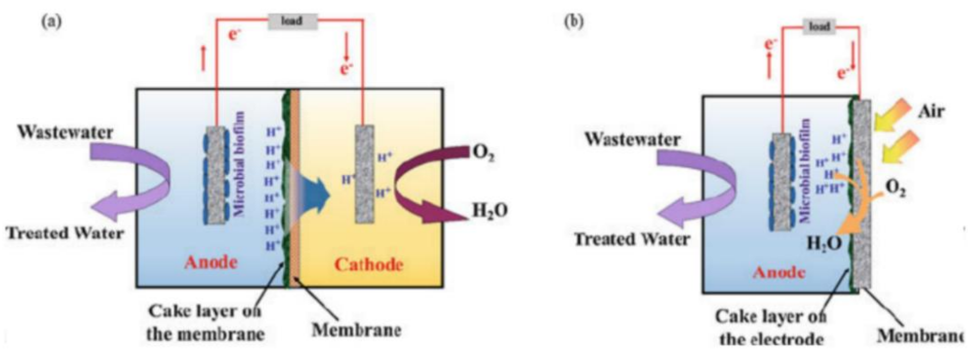

Figure 1. MFC structure of (a) double chamber and (b) single chamber

3. Application

3.1 Wastewater Treatment

Using MFC to treat wastewater can realize a one-step conversion from wastewater to electricity. The principle is to use microorganisms as catalyst to degrade pollutants in water while delivering electrical energy. Double chamber MFC is the most typical one. In the anode chamber, the organic matter contained in wastewater is mainly used as a carbon source and electron donor by anode microorganisms (Wang et al., 2014). About 22%~30% are the net electric energy output, and the remaining energy consumption is due to unoxidized electron donors, microbial anabolism, cathode regeneration and so on. Anode mainly treats easily biodegradable wastewater, such as municipal wastewater and food processing wastewater. In the cathode chamber, the pollutants collect electrons on the cathode surface to reduce and become pollution-free or low-toxicity substances, such as dye wastewater (Zhai & et al., 2016). Or indirect reduction reaction occurs, i.e., using microorganisms as biocatalysts to build biocathodes, which is mainly used to treat pollutants that are difficult to be reduced, such as nitrogenous wastewater and heavy metal wastewater (Sun, 2009).

Compared to the traditional wastewater treatment, MFC does have higher degradation efficiency, but there are still some limitations and bottlenecks. Firstly, expensive electrode materials and membrane pollution will lead to high costs and complex operations. What's more important, thermodynamic barriers and high-power losses limit the actual power generation potential of MFC. According to the research by Zhai et al. (2016), the maximum power density and power level of MFC are 200W /m^3 and 0.2MW per 1,000 m^3, respectively, which is many orders of magnitude lower than other energy conversion technologies, and thus, cannot be used as a stationary power source to meet local demand (Figure 2).

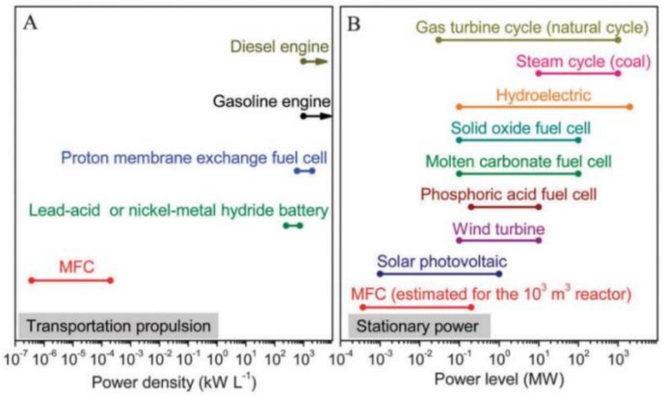

Figure 2. Power density and power level between MFC and other energy conversion devices

3.2 Microbial Electrolysis Cell

Coupling with other technologies can enhance the utility of MFC functionality. MFC can run in microbial electrolysis cell (MEC) mode. In an MFC-MEC coupled system, biological energy from the anode is pooled to meet additional power demand and overcome thermodynamic barriers from protons to hydrogen. Its advantage is to produce H_2 from waste and store them, compensating for the low power density of a single MFC system. The experiment by Rozendal et al. (2009) proved that cathodic hydrogen peroxide (H_2O_2) production is feasible and efficient by a combination of oxygen reduction and microbial oxidation of anode organic matter, which can produce H_2O_2 from acetate with an efficiency of 83%.

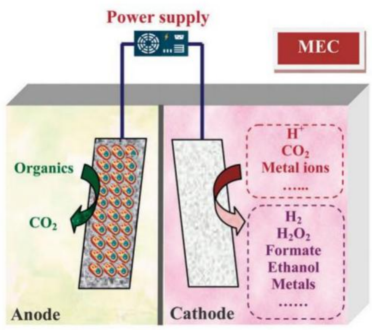

Figure 3. Working principle of MEC system

3.3 Microbial Desalination Cell

Microbial desalination cell (MDC) is also called intermedium chamber wastewater treatment. A potential gradient at the anode and cathode is generated by using chemical energy stored in organic matter to achieve the purpose of desalination (Di Lorenzo & et al., 2009). In general, the anode chamber is in charge of organic degradation and power generation, the intermediate chamber is used for ion separation, and the cathode chamber completes the circuit loop (Zhai & et al., 2016). Unlike other desalination technologies requiring power inputs, MDC technique is better at obtaining pure water from seawater while generating net energy from waste. According to the research by Jacobson et al. (2011), 1L of upward flowing MDC can reduce the salinity of 1 cubic meter of seawater by 90% while generating 1.8 kWh of energy, compared to the 2.2 kWh of energy required to recover 50% of the water in a reverse osmosis system.

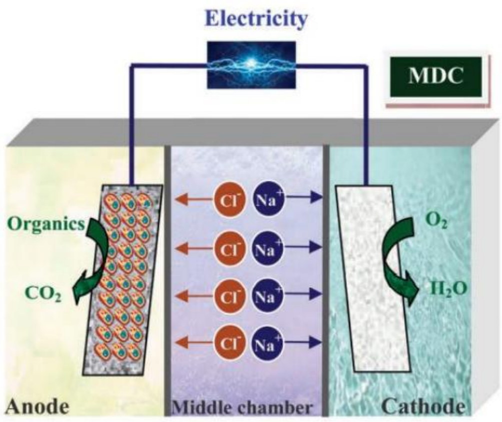

Figure 4. Working principle of MDC system

4. Conclusion & Outlook

As a clean energy technology that can realize synchronous sewage treatment and electric energy recovery, MFC represents the future development direction of wastewater resource recovery and has broad development prospects. To maintain the good performance of MFC, the choice of battery configuration, electrode material and exchange membrane is very significant. The output power of single-chamber MFC is high, but the coulomb efficiency of air cathode is low, which restricts its practical production and application. Electrode materials are expensive, especially platinum catalysts. Furthermore, coupling MFC with other technologies can enhance the practicability of MFC functions, make up for its shortcomings, and expand the application range of MFC, such as MED and MDC. In particular, a significant advantage of the MEC is the ability to compensate for the instability of the anode output by adjusting the strength of the external energy supply.

Based on the bottleneck of MFC, it is suggested to conduct in-depth research in the following aspects in the future: (1) Modification of conventional exchange membranes or search for suitable membrane replacement materials to improve the performance of MFC; (2) The development of new anode materials with low resistance, corrosion resistance, high porosity and high specific surface area is also critical to expanding the range of MFC applications; (3) Single chamber MFC air cathode material still needs to be explored; and (4) While widening extent of applications, the strategy of MFC power utilization in situ should be explored to encourage the combination of MFC with other low-energy technologies.

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