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A Review of Its Development, Design, and Power Generation on Microbial Fuel Cell

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Abstract: Microbial fuel cells (MFCs) are a promising technology that use microorganisms to generate electrical energy from chemical energy. However, ultralow-power production and high-cost materials have become significant drawbacks in MFC development. Therefore, various methods have been proposed for increasing the output power of MFC. Among them, stacking multiple cells in a series has been suggested as the most promising method for generating high power in MFC. However, voltage reversal (VR) has become an issue that limits the electrical power generation in stacked MFC. Thus, this study investigates and discusses the actual cause of the voltage reversal phenomenon in a series-stacked MFC from the perspective of electron and proton transfer mechanisms. This paper also discusses the electronic control methods used to eliminate VR and challenges in MFC development.

Keywords: Microbial fuel cell, Series-stacked, Substrate concentration, Voltage reversal.

1. Introduction:

Constructed wetlands (CWs) are artificial systems that were designed and constructed to utilize the natural processes involving wetland vegetation, soils, and their associated microbial assemblages to purify wastewater[1]. They were often used for removing of organic matters and nutrients contained in wastewater[2]. For its low cost, coexistence with an inner aerobic/anaerobic environment, a high specific surface area of the matrix, a long hydraulic retention time (HRT) et.al.[3], constructed wetlands were regarded as a promising technology. However, with the running time increasing, constructed wetland suffers from a progressive media obstruction, so-called clogging process[4], causing the treatment performance degradation. It has become an urgent problem in recent years. Nowadays, the study of microbial fuel cell (MFC) has been more and more popular. Progresses have been made in the MFC research and some review articles on the microbial fuel cell are available[5]. Compared with conventional wastewater treatment processes, MFC is an energy-harvesting platform incorporated into renewable energy stored in organic substances, particularly in wastewater, to produce bioelectricity and simultaneous wastewater treatment[6]. That is, it can convert chemical energy from organic matter into electrical energy by certain bacteria[7].According to previous study, Chemical energy that the wastewater contains is nine time more than the energy that is spent on purifying it in conventional wastewater treatment processes[8]. Thus, focusing on how to recycle and utilize this energy by the MFC has been more widely concerned[9].

Excessive energy demands and environmental contaminants have accelerated the research and development of renewable and sustainable energy sources [1]. Currently, solar, biogas, wind, fuel cell, hydro, and geothermal energy generation technologies are commercially available as replacements for fossil fuels that support the current energy demand [2]. Among other alternatives, microbial fuel cells (MFCs) are becoming popular, using exoelectrogens to generate electrical energy while removing pollutants [3]. However, the development of MFCs as viable energy sources faces many challenges. The core direction in MFC research includes methods to improve electrical power generation in MFC systems, control of unstable MFC voltage, mitigation of multiple losses in the design, detection, and prevention of the voltage reversal phenomenon, and utilization of low-cost materials [2], [4] In this review, an extensive overview of different aspects of MFCs, including their evolution, design considerations, mechanisms of energy generation, stacking, voltage reversal phenomena, and attempts to enhance MFC performance, is presented and discussed.

2. Related Work:

An MFC uses the basic concept of a Galvanic Cell, which generates electrical energy directly from chemical energy with the aid of microorganisms [5], [6]. The term MFC was first proposed in 1962 by Davis and Yarbrough in their paper ``Preliminary Experiment on a Microbial Fuel Cell." They observed that microbes react with hydrocarbons to produce electrical energy [7]. However, the initial research that led to MFC began in the early 18th century with the birth of galvanic cells by Luigi Galvani. The idea of generating electricity from chemical reactions was started by Luigi Galvani and Alessandro Volta at the end of the 18th century [8], [12]. However, the idea of using microorganisms to generate electricity was initiated by Potter [13] in 1911 with the experimental setup illustrated. In his experiment, the nutrient fluidwas filled with a microorganism culture in a glass jar. A platinum electrode was immersed inside the nutrient fluid, which acted as the anode. The same material was used as a cathode dipped into the liquid inside the porous cylinder, which acted as a proton exchange membrane (PEM). When the C-A terminal is closed, current flows from the cathode to the anode, charging the capacitor. When the C-B terminal of the switch is closed, the capacitor is discharged through a galvanometer [13]. However, no analysis has been performed to understand the details of the proton and electron transfer mechanisms. Davis and Yarbrough explored the role of microbes that use hydrocarbons as their food to generate electrical energy. In this experiment, a different type of reactor was designed and divided into three main parts. The left-hand side is called a biological half-cell, supplied with continuous nitrogen. The middle part is called the buffer zone and is bubbled with Oxygen-free Nitrogen to prevent oxygen from reaching the biological half-cell. The right-hand side is called the oxygen half-cell, bubbled continuously with oxygen. All three compartments were filled with 1% Sodium Chloride (NaCl) with 0.05 M Phosphate buffer at pH 7. Experimental Setup by Davis et al. Illustration by author. reported three different types of experiments using (a) Glucose Oxidase, (b) Escherichia Coli, and (c) Nocardia as added microbes in the glucose substrate using a 1000 ohms load. The experiment shows that using microorganisms generates a higher voltage than the usual solution [7]. The MFC design introduced by Davis. Research on MFC exploded when NASA announced a study to develop a fuel cell that used human waste to generate electricity in 2004 [14]. In 2006, researchers from the University of Florida investigated the possibility of converting human waste into methane to produce electricity in space [15].

The structure and evaluation parameters of MFC-CWs. As a MFC, the MFC-CW consists of an anode compartment, a cathode compartment and an external circuit. The anode oxidizes organic compounds by electrochemically active microorganisms to release electrons and protons[11]. Then, electrons transfer to the cathode through the external circuit and generate electric currents. By measuring the produced current densities of MFC-CWs, wastewater treatment efficiencies are determined. It should be noted that electrochemically active microorganisms are anaerobic. However, oxygen usually acted as the electron acceptor in cathode, and the cathode must be aerobic. Additionally, the electrodes would be planted with aquatic plants in some MFC-CWs. Plants possess the unique ability to release oxygen as well as root exudates into the rhizosphere, and the excreted oxygen from plant roots could be used as a viable alternative source of electron acceptors for MFCs[12]. Liu et al. (2014)[13] pointed that wetland plant roots could be placed in the anode zone or cathode zone of an MFC, and they were both beneficial to power generation.

Rhizosphere-anode CW–MFC is appropriate for treating low concentration organic wastewater, while the Rhizosphere-cathode CW–MFC has the ability of resisting high organic loading rate. In general, recognized evaluation indicators of MFC-CWs are Coulomb efficiency (CE) and power density. CE is on behalf of the proportion of anodic organic compound which is loss of electrons. The higher of the electrons produced, the higher the CE is. The power density is the maximum power that per unit area electrode (anode or cathode) or per unit volume of liquor can output. It is positive relationship between the performance of MFC-CWs[3]. Comparing the performances among different structures of MFC-CWs depends on the size of the coulomb efficiency and power density.

Influence factors of MFC-CWs. There are many factors affecting the performance of the MFC-CWs, such as pH, electron donors, electron acceptors, the electrode materials, electrode spacing, the matrix, influent factors, operation parameters and the presence of plants et al. For example, Zhou et al.(2013)[14] tested the performance of MFC-CWs for decolorization of azo dye and bioelectricity generation. The result indicated that the planted CW-MFC system achieved the highest decolorization rate of approximately 91.24% and a voltage output of approximately 610mV. Concluding that plants grown in cathode compartment enhanced the cathode potential and slightly promoted dye decolorization efficiency. Besides Villaseñor, J. et al.(2013)[15] conducted an experiment that the MFC-CW worked under continuous operation for 180 d, treating three types of synthetic wastewater with increasing organic loading rates of 13.9g COD/m2·d, 31.1gCOD/m2·d and 61.1gCOD/m2·d. The results indicated that under low organic loading rates, the wastewater organic matter was completely oxidized in the lower anaerobic compartment, and there were slight aerobic conditions in the upper cathodic compartment, thus causing an electrical current. However, under high organic loading rates, the organic matter could not be completely oxidized in the anodic compartment and flowed to the cathodic one, which entered into anaerobic conditions and caused the MFC-CW to stop working.

Oliveira et al. (2013)[5] pointed that pH had an effect on the MFC-CWs because the anode reaction released protons that will flow to the cathode compartment, which caused the increasing of pH in the cathode compartment. Current generation can significantly decrease according to the

Nernst equation. Organic compounds which are oxidized decline affecting performance of MFC-CWs. Similarly, Zhang et al.(2016)[16] studied the effect of electrode material on the MFC. The findings from this study suggest that the rGO/MnO2/CF anode, fabricated via a simple dip-coating and electro-deposition process, could be a promising anode material for high-performance MFC applications.

Furthermore, Liam et al.(2015)[17] studied the effect of electrode spacing and flow direction on the performance of microbial fuel cell-constructed wetland. By placing the cathode at the air-water interface and burying the anode at a depth of 0.4m, the amount of dissolved oxygen at the cathode area is increased while ensuring the anode remains anoxic. He held that the ohmic resistance was reduced keeping the anode buried and placing the cathode directly above. Electrode spacing is attached a high importance to enhance performance of generate electricity, which is related to internal resistance. It is essential to enhance removal efficiency of pollutants via lowering the internal resistance.

Nowadays, we seek energy sources that are high-effective, eco-friendly, and renewable to substitute the fossil fuels [5, 18, 19], MFC-CWs is potential and will be more widely applied in the future. However, it is still a long way to go before the MFC-CWs are practical applied. There are a lot of problems in the need to be solved. Such as the clogging of MFC-CWs, Clara Corbella et al. (2016)[20]considered the microbial fuel cell coupled with horizontal subsurface flow constructed (HSSF CW) wetland to show a result that although longer study periods under more realistic conditions shall be further performed, the HSSF CW operated as a MFC has great potential for clogging assessment. In addition, especially, the recent studies indicated that the power density of MFC-CW is much lower than the traditional MFC for the smaller reactor volumes. The most reactor volumes of MFC-CW are still in the centimeter level, from 1.4L to 96L range[21]. However, the increased reactor volume might result in the decreasing of power density [21, 22]. For solving this problem, increasing the electrode ratio of the volume accounting, or the shrink electrode spacing, exploring multistage MFC-CWand operation mode are alternative methods.

Generally, many biological, chemical, physical, and electrical parameters inuence the electricity generation in MFC. A powerful MFC-based energy-harvesting system can be developed if these parameters are optimally maintained with sufficient modifications and existing resources [3]. The substrate concentration and reactor design are the most important elements influencing the output of MFCs. Temperature, pH, type of microorganism, substrate mixing, membrane selection, and feeding duration were also reported as other elements.

3. Conclusion:

Despite many challenges, MFCs have considerable advantages in replacing the current electrical energy generation for various applications. MFCs are the only technology that can remove pollutants while producing electrical energy directly from chemical energy. The drastic change in research and development of MFC in the last 20 years shows the growing popularity of this technology among researchers. Removal of pollutants while generating electricity, direct chemical to electrical energy, performance under mild conditions, easy customization, no sludge aeration, lower sludge treatment, self-regeneration of microorganisms, and water reclamation are some advantages of MFC.

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