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Design and Analysis of a Photocatalytic Microbial Fuel Cell System Using a C-TiO_2 Anode for the Synergistic Treatment of Composite Pollution in Mine Water and Power Generation

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Abstract

Mine drainage is a typical type of wastewater generated throughout mining activities, which commonly contains persistent organic contaminants represented by bisphenol A, as well as heavy metal ions including iron, manganese and zinc. Improper discharge and treatment of such wastewater will lead to severe ecological environmental pollution and massive waste of available water resources. Although traditional wastewater treatment techniques are capable of eliminating partial pollutants from mine drainage, they are restricted by inherent defects such as high energy consumption, expensive operating cost and low resource recycling efficiency. Microbial fuel cells (MFCs) can realize in-situ electricity generation relying on microbial biodegradation of organic pollutants, achieving synchronous pollutant removal and energy recovery. Nevertheless, the practical application of conventional MFCs is still hindered by unsatisfactory power output, mainly stemming from low interfacial electron transfer efficiency and inferior long-term system stability. Targeting these key technical limitations, this work constructs a novel double-layer eight-chamber MFC system integrated with TiO_2 photocatalysis technology. The double-layer eight-chamber structural design effectively enlarges the overall reaction space of the reactor and accelerates the electron transfer rate inside the system. Moreover, the introduced TiO_2 photocatalysis module further improves the degradation efficiency of refractory organic compounds and the removal capacity of coexisting heavy metals. The systematic analysis on reactor structure configuration, internal working mechanism and pollutant removal pathways demonstrates that the integrated hybrid system can efficiently purify mine drainage polluted jointly by bisphenol A and heavy metals, while achieving stable bioelectricity generation. This research provides a novel feasible technical solution for harmless treatment and resource reuse of mine drainage, as well as theoretical and technical support for the construction of green and low-carbon mining ecosystems.

Keywords

Microbial fuel cell, titanium dioxide photocatalysis, mine water, bisphenol A, and heavy metals.

1. INTRODUCTION

Mining activities inevitably generate large volumes of mine wastewater, which is regarded as a typical hazardous wastewater source in the mining industry [1]. Characterized by intricate chemical compositions, such wastewater not only contains suspended solids and abundant inorganic salts, but also accumulates recalcitrant organic contaminants like bisphenol A (BPA), together with heavy metal ions including iron, manganese and zinc [2]. Direct discharge of untreated mine wastewater into surrounding water and soil environments will bring long-term

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irreversible damages to local ecological systems, and also endanger human health through food chain transmission and daily exposure.At present, mainstream conventional techniques for mine wastewater treatment mainly consist of coagulation sedimentation, adsorption, membrane separation and biodegradation [3]. Despite capable of removing most target pollutants to meet preliminary treatment demands, these conventional approaches still face prominent limitations in practical engineering applications, such as huge power consumption and high daily operation and maintenance costs. As a promising sustainable wastewater treatment technology, microbial fuel cells (MFCs) can realize wastewater purification and electricity generation simultaneously. Even so, poor electron transfer efficiency and unsatisfactory power output performance still hinder the further popularization and industrial application of standalone MFCs in mine water remediation [4]. Titanium dioxide (TiO_2) photocatalysis has been proven to be highly efficient in degrading refractory organic pollutants, owing to its strong photocatalytic oxidation capacity. Given the respective strengths and deficiencies of TiO_2 photocatalysis and MFCs, this study established a novel coupled system by integrating TiO_2 photocatalytic modules with an eight-chamber double-layer microbial fuel cell. The hybrid system aims to optimize electron transfer pathways and enhance photocatalytic oxidation reactions. In this way, it can achieve higher removal efficiencies of organic pollutants and heavy metals in mine wastewater, while accomplishing efficient energy recovery during the whole wastewater treatment process.

2. CURRENT STATUS OF RESEARCH ON THE TREATMENT OF MINE WATER USING MICROBIAL FUEL CELLS

2.1. Basic Principles of Microbial Fuel Cells

A standard microbial fuel cell (MFC) consists of four core components: an anode chamber, a cathode chamber, a proton exchange membrane and an external circuit [5]. Electroactive microorganisms attached to the anode surface are able to degrade organic pollutants in wastewater. Electron and proton release takes place concurrently during microbial organic degradation. The released electrons flow to the cathode via the external circuit, thereby producing continuous electric current. In parallel, protons migrate through the proton exchange membrane to the cathode and engage in cathode reduction reactions, with water formed as the final product. Pollutant removal and electrical energy recovery can be completed synchronously throughout the whole reaction process. Benefiting from such a distinctive working principle, MFCs are able to mitigate wastewater contamination and capture renewable bioenergy at the same time. Accordingly, MFC technology has emerged as a competitive bifunctional approach for wastewater bioremediation [6].

2.2. Current MFC Configurations and State of the Art

Existing microbial fuel cells have three mainstream structural layouts, namely single-chamber, dual-chamber and stacked MFC setups [7]. Single-chamber MFCs have a simple framework and low construction costs.Even so, their cathode sections are prone to accumulate pollutants easily, which harms the stable long-term operation of the entire system.Separating the anode and cathode zones allows dual-chamber microfluidic devices (MFCs) to operate more smoothly.But their limited reactive surface area limits the transfer speed of electrons, causing unsatisfactory efficiency.For stacked MFCs, they can produce higher output voltage and current, but they experience severe internal resistance loss during operation [8].

Recent years have drawn a growing interest in Multi-chamber MFC configurations.Adding more reaction units effectively increases the wastewater treatment capacity and the power generation performance of the device.Even though there is this advantage, current multi-

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chamber MFC designs still have obvious issues, like complicated assembly structures and hard daily maintenance work.

2.3. Research Progress on MFC Treatment of Mine Water

Microbial fuel cells can cut down COD, ammonia nitrogen and several heavy metals contained in mine wastewater to a satisfying extent, alongside generating electric power in the meantime. Heavy metal ions get removed chiefly through three pathways: electrochemical reduction, biosorption and chemical precipitation. On the contrary, the system can hardly reach ideal treatment outcomes when tackling refractory organic pollutants like bisphenol A. Insufficient electron utilization efficiency and weak electricity output capacity act as major bottlenecks that stop MFC technologies from being applied on a broader scale.

3. DESIGN OF A DOUBLE-LAYER, EIGHT-CHAMBER MFC

3.1. Structural Design

The system proposed in this paper primarily consists of a double-layer, eight-chamber microbial fuel cell and an external 300W xenon lamp serving as the light source. The cell reactors are made of acrylic glass, with cathode and anode chambers arranged in an alternating pattern and stacked vertically. Each chamber is a square with identical volume. Water inlet ports are located at the bottom of each reaction chamber; water is pumped from the bottom upward and discharged through the outlet ports at the top. Adjacent reaction chambers are separated by a proton exchange membrane. Electrode mounting holes are provided near the connection surfaces for electrode fixation and wire connections. The cathode electrode uses carbon cloth, while the anode electrodes use C-TiO_2 composite electrodes of the same size. After installation, acclimatized activated sludge is mixed with anode solution and injected into the anode chamber, and 0.5 mol/L potassium ferricyanide is injected into the cathode chamber. Under the action of microorganisms, pollutant degradation and electron generation are completed. Reaction units on the same layer are connected in parallel, while upper and lower layers are connected in series. The system is ultimately connected to an external data acquisition system to enable real-time monitoring of operating parameters.

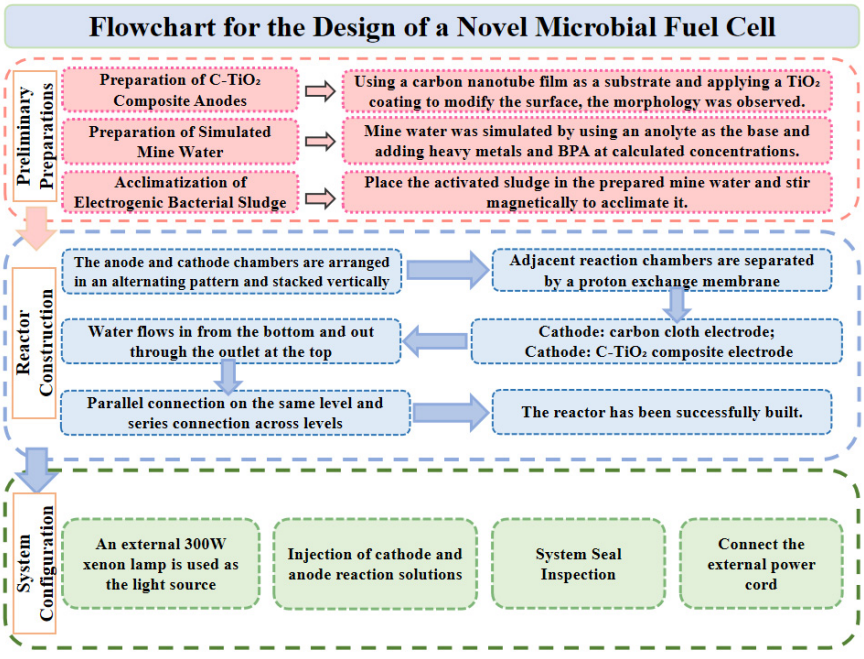

Figure 1. MFC Design Flowchart

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3.2. Structural Advantages

This newly designed reactor is equipped with multiple shared anodes and cathodes while taking up far less installation space. More pairs of anode and cathode also accelerate the migration rate of ions between two electrodes. When multiple basic structural units are connected in parallel, the whole system can produce stronger and more steady electric current. Besides, the photocatalytic property of C-TiO_2 modified anode works synergistically with electroactive microbes inside the microbial fuel cell. Such mutual promotion greatly boosts the degradation of bisphenol A as well as the elimination of heavy metal contaminants.

4. ANALYSIS OF EXPECTED TREATMENT PERFORMANCE

4.1. Expected Pollutant Removal Efficiency

It is projected that the double-layer eight-chamber layout can raise the contact probability between microorganisms and pollutant substances inside the reactor. TiO_2-based photocatalysis brings two major benefits here: it greatly speeds up the breakdown of bisphenol A, and simultaneously eliminates heavy metal elements including iron, manganese and zinc via precipitation, adsorption and oxidation reactions. The overall removal rate of these metal contaminants can exceed 80%, which proves the integrated system holds great practical prospects for treating bisphenol A and heavy metal pollution at the same time.

4.2. Expected Power Generation Performance

The design with multiple reaction units is capable of boosting electron generation and speeding up ion migration between anodes and cathodes. Rational series-parallel connection of each unit can deliver far steadier electric current. It is estimated that this system outperforms conventional single-chamber and dual-chamber MFCs in power generation, with output voltage expected to surpass 1.0 V.

5. APPLICATION PROSPECTS AND OUTLOOK

The integrated system combining TiO_2 photocatalysis and double-layer eight-chamber microbial fuel cell can purify simulated mine wastewater while generating electricity simultaneously. It shows great promise for practical wastewater treatment scenarios in future engineering applications. But there a few bottlenecks that need to be resolved, like the complicated structural assembly, low photocatalytic activity, and high electrode material costs.To enhance the pollutant removal and power generation capacities of the entire system, we need to make further electrode modifications and regulate the microbial community.

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