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WASTEWATER TREATMENT AND ENERGY PRODUCTION USING A BAFFLED MICROBIAL FUEL CELL

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ABSTRACT

Microbial fuel cells (MFCs) convert chemical energy into electricity through catabolic activities of exoelectrogenic bacteria under anaerobic conditions, and have a great self-sustainable potential of converting wastewater to electric power and a cost-effective approach for environmental sustainability. However, the performance is still far from the expected levels, and researchers continue to improve the performance of MFCs. Even though many different configurations are possible for the MFCs in either batch or continuous flow operation mode, MFCs in complete mix in batch mode configuration extensively studied in lab scale systems because of simplicity of construction and operation, where theoretically a uniform substrate concentration achieved in the systems. Recent studies confirmed that other rector configuration also succesfully can be applied into MFCs. One of them is Anaerobic Baffled Reactor (ABR) which is consisted of a series of vertical baffles to force the wastewater to flow under and over baffles as it passes from the inlet through outlet. Applying these reactors to MFC technology has a lot of potential for being developed into efficient applications. In this study, two types of MFCs configuration BPF-MFC and PF-MFC that simulate the existing wastewater treatment processes have been developed and compared in batch mode and continuous flow mode to investigate MFC performances. The results showed that the BPF-MFC has higher substrate removal than the PF-MFC. The maximum COD removals up to 88% and 74% were obtained with initial COD concentrations of 1000 mg/L in BPF-MFC and PF-MFC reactors, respectively. Moreover, when we compare the power generation in the both BPF-MFC and PF-MFC reactors, it is clearly shown that the BPF-MFC has better power density response under the same conditions. Therefore, this study showed that the flow pattern in the MFC reactors is one of the crucial factors that directly effects performances.

Keywords: Wastewater treatment, microbial fuel cell, baffled reactor

INTRODUCTION

Microbial fuel cells (MFCs) convert chemical energy into electricity through catabolic activities of exoelectrogenic bacteria under anaerobic conditions, and have a great self-sustainable potential of converting wastewater to electric power and a cost-effective approach for environmental sustainability (Logan, Hamelers et al. 2006, Du, Li et al. 2007). A typical MFC consists of two chambers, an anode and a cathode chamber, which are usually separated by a membrane (i.e. a cation exchange membrane, CEM). Therefore, the main components of a MFC are two electrodes materials (anode and cathode) and electrolyte. In the anodic compartment, electrochemically active bacteria oxidize organic matter to generate electrons and protons. The generated electrons are transferred to electrodeIn the meantime, the protons diffuse from the anode to the cathode through a separator. At the cathode, the electrons combine with the protons to reduce the electron acceptor (usually oxygen) (Logan, Hamelers et al. 2006). With the increasing number of publications in the last two decades, researchers have demonstrated that this technology could be useful for the powering of electronic devices, wastewater treatment, removal of pollutants, and biosensors (Shantaram, Beyenal et al. 2005, Aelterman, Rabaey et al. 2006, Donovan, Dewan et al. 2008, Tender, Gray et al. 2008, Kelly and He 2014). Even though much of MFCs research was focused on power generation and maximizing power densities, it has recently been recognized that MFCs have a high potential to treat wastewater. Therefore, it is critical to investigate how to improve wastewater treatment efficiency using MFCs.

The high-rate wastewater treatment efficiency from the application of anaerobic technologies critically depends on the development and operation of high-rate anaerobic bioreactors. In general, three types of reactors are mainly used in wastewater treatment systems, which are Batch (BR), Plug Flow (PF) and Complete Mixing (CM) reactors. The influent and effluent of flow rate for the BR are the same. The PF systems are designed as narrow long channels, so reacting material to take a longer path through the reactor. On the other hand, perfect mixing is assumed for the CM systems to achieve a uniform reactants and products concentration in the systems (Metcalf, Eddy et al. 1991, Tchobanoglous, Burton et al. 2003). Even though many different configurations are possible for the MFCs in either batch or continuous flow operation mode, MFCs in complete mix in batch mode configuration extensively studied in lab scale systems because of simplicity of construction and operation, where theoretically a uniform substrate concentration achieved in the systems (Logan, Hamelers et al. 2006, Logan 2008, Jiang, Li et al. 2010, Jiang, Curtis et al. 2011). On the other hand, PF configuration was investigated in a few fundamental studies, where reacting material takes a longer pathway through the reactor with the gradient of COD concentrations along the length of the reactor (Min and Logan 2004, Karra, Troop et al. 2013, Feng, He et al. 2014, Dimou 2017). However, it is important to reach at least the same wastewater treatment efficiency with the conventional systems to get the benefit of this technology. Besides the basic classification of the chemical reactors, high-rate anaerobic bioreactors can be also classified into three groups depending on biomass mechanisms including attached growth, suspended growth, and hybrid. In 1981, McCarty and co-workers discovered that the biomass in Rotating Biological Contractor was actually suspended, not attached, and they removed the rotating discs, so initialized a new reactor design. Later, Bachmann, Beard and McCarty developed one of the innovative reactor designs by modifiying Upflow Anaerobic Sludge Blanket (UASB) reactor in 1983 (Bachmann, Beard et al. 1982). They named the new reactor as Anaerobic Baffled Reactor (ABR) which is consisted of a series of vertical baffles to force the wastewater to flow under and over baffles as it passes from the inlet through outlet (Nachaiyasit and Stuckey 1995). In time several modifications have been made and previous studies show that among the modern high-rate reactors, the ABR is a promising and effective reactor design for both industrial and domestic wastewater (Boopathy, Larsen et al. 1988, Polprasert, Kemmadamrong et al. 1992, Nachaiyasit and Stuckey 1995). Applying these reactors to MFC technology has a lot of potential for being developed *into* efficient *applications.* One of the very first demonstrations of baffled-reactor MFC was conducted by Li et al. by modifying a membranless single-chambered air cathode MFC. One of the very first demonstrations of baffled-reactor MFC was conducted by Hu et al. by modifying a membranless single-chambered air cathode MFC. This study aimed to increase coulumbic efficiency by enabling to formate of thick cathodic biofilm formation to restrict oxygen transfer by adding a baffle between the anode and cathode to reduce mixing around the cathode.

Different from previous studies, this study focus on increasing wastewater treatment performance besides power generation using baffled-reactor MFC. Two types of MFCs configuration BPF-MFC and PF-MFC that simulate the existing wastewater treatment processes have been developed and compared in continuous flow mode to investigate MFC performances.

MATERIALS AND METHODS

The microbial fuel cells configuration and operation

Membranless baffled plug flow MFCs (BPF-MFCs) and complete mix MFCs (PF-MFCs) with multi anode-cathode were used in this study. The BPF-MFC and CM- MFC systems (volume: 300 ml) had six anodes (carbon fiber brush-fiber diameter: 2.54 cm; carbon fiber brush length: 2.54 cm, Mill-Rose Carbon Fiber Brush Anode) and six cathodes (platinum doped, 10% by weight on carbon black (0.5 mg/cm^2), surface area: 2.5 cm^2/cathode) located from the anodes. The outside of carbon cloth which exposed to air was sealed with gasket to cut off the oxygen diffusion to the cathode. Each system was divided into six identical channels along the flow pathway (each channel volume approximately: 50 ml) and BPF-MFC has using closed baffles with openings (the area of baffle opening: 1 cm^2), to minimize bypass. The influent wastewater entered to the channels (the influent tubing diameter: 0.635 cm) and flowed sequentially through each channel. Each anode-cathode pair was connected individually to an external resistor. There were 12 external circuits totally (Figure 1). An external resistance ($R_{ext.}$) of 510 Ω was used for all SCMFCs. The voltage over the R_{ext} was recorded every 2 hours using a Keithley

2700 data logging system. The tests were conducted with a controlled temperature of 25±2 °C. Influents were pumped to the MFC systems using two identical peristaltic pumps (Cole Palmer, Masterflex L/S) and controlled by a programmable timer (ChronTrol XL). The MFC systems were operated at 25 ℃.

Inoculation and operations

The BPF-MFC and PF-MFC were inoculated with the influent to the municipal wastewater. Sodium acetate was added to the raw wastewater feed as the organic substrate and BPF-MFC and PF-MFC were operated with different initial sodium acetate concentration to investigate the effects of substrate concentration (chemical oxygen demand: COD) and on MFC performances. After three weeks of enrichment at batch mode, a stable power production was achieved and BPF-MFC and PF-MFC systems were then switched to the continuous mode. The reactors were operated in continuous mode for a 3-week period with two different hydraulic retention time (HRT) of 10 h.

Analytical methods

The power density was determined by changing the R_{ext} (10 Ω to 2940 Ω) and measuring the voltage over each R_{ext} with a multimeter (Radioshack digital multimeter). The polarization curve was plotted to determine the R_{in} and the power generation at different R_{ext}. The internal resistance was calculated from the slop of V-I curves. Based on R_{ext} and V, the current density generated was calculated according to $I = V/A \times R_{ext}$, and the power density was calculated according to $V^2/A \times R_{ext}$.

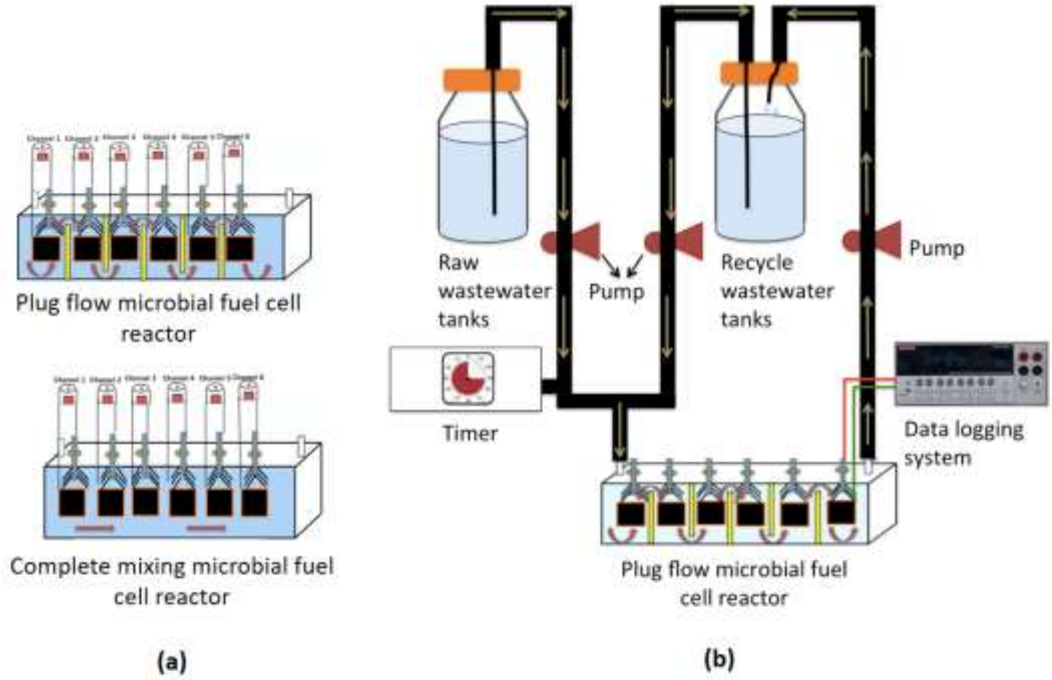

Figure 1. Schematic diagram of (a) the microbial fuel cell reactors including anode and cathode electrodes; (b) experimental setup including data logging system, timer, wastewater tanks inlet and outlet with flow direction of wastewater (drawing is not to scale).

The concentration of the organic compounds in the anodic chamber was evaluated weekly. The dissolved COD was determined using mercury-free potassium dichromate method (low range and high range COD 2 vials, Hach Company, Catalog # 2565025 and 2565115, respectively, Loveland, CO, USA) with DR 220 spectroscopy (HACH, Loveland, CO, USA) following the standard HACH procedure.

RESULTS AND DISCUSSION

Effects of the reactor configuration on power density

The power density of BPF-MFC and PF-MFC was examined at the COD concentrations of 1000 mg/L and HRT of 10 hr for Channels I, III, and VI. The power generation curves showed that the average power density of BPF-MFC increased with time, and decreased along the wastewater flow pathway in the reactor. The data shows the average of 3 weeks of operation that the peak power densities of 232.5 mW/m^2, 205.1 mW/m^2, and 185.2 mW/m^2 in Channels I, III, and VI, respectively (Fig. 2a). The overall average power densities 137.2 mW/m^2, 127.6 mW/m^2, and 106.5 mW/m^2 in Channels I, III, and VI, respectively. The slightly increase in power generation in Channel I can be explained with COD concentration since the wastewater encounters with the anode-cathode electrode pairs in the BPF-MFC reactor for the first time here, so more substrate available for the exoelectrogenic bacteria. Another reason can be related with the biomass settling from wastewater because of the long HRT in BPF-MFC reactor. On the other hand, Fig. 2b shows the power density of PF-MFC. Because of the reactor configuration, PF-MFC reactors provides uniform substrate concentration inside the reactor. The data shows the peak power densities of 205.6 mW/m^2, 196.7 mW/m^2, and 188.1 mW/m^2 in Channels I, III, and VI, respectively (Fig.2b). The overall average power densities 137.2 mW/m^2, 127.6 mW/m^2, and 106.5 mW/m^2 in Channels I, III, and VI, respectively. When we compare the power generation in the both BPF-MFC and PF-MFC reactors, it is clearly shown that the BPF-MFC has better power density response under the same conditions.

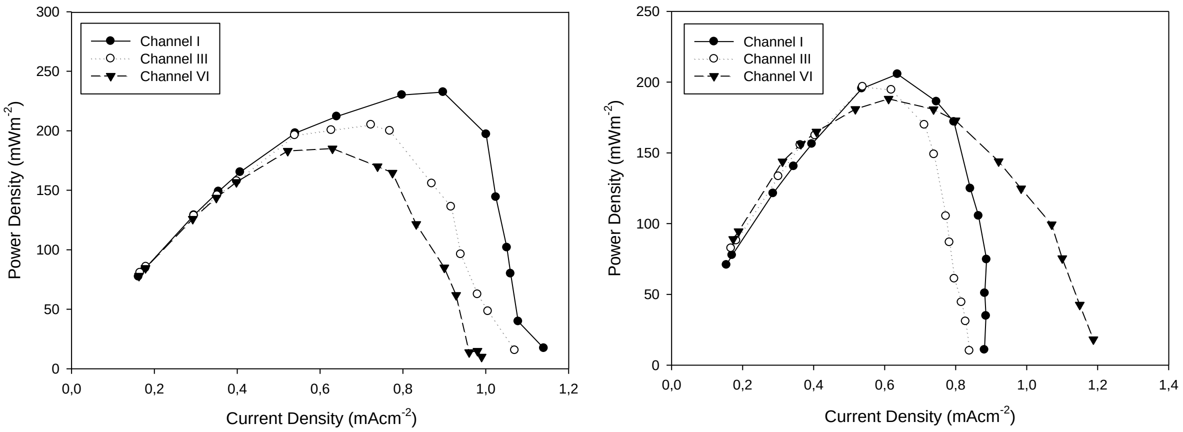

Figure 2. The power generation curves of (a) the BPF-MFC; (b) the PF-MFC after 3 weeks of operational period. The data are means, and the error bars represent the standard deviations of the means from two biological replicates.

Effects of the reactor configuration on COD removal efficiency

After three weeks of enrichment period, the BPF-MFC and PF-MFC were fed with acetate-based wastewater and operated continuously for 30 days to analyze COD removal efficiencies. The COD removal efficiencies (%) were shown in Figure 3 in Channels I, III, and VI respectively in the BPF-MFC and PF-MFC reactors. Maximum COD removals up to 88% and 74% were obtained with initial COD concentrations of 1000 mg/L in BPF-MFC and PF-MFC reactors, respectively. The higher COD removal efficiency of BPF-MFC might be explained by having baffles in the MFC might provide uniform distribution of organic matters throughtout the reactors. We also conducted the statistical ANOVA test to examine if there was a significant impact of different channels and also reactor type on COD removal rates. The p-values of channels of BPF-MFC and PF-MFC reactors from the test were 0.770 and 0.873, respectively. In addition, the p-values of BPF-MFC and PF-MFC reactors was found 0.567, suggesting that differences in different channels and reactor type had no significant impact on COD removal rates. These results also demonstrated that BPF-MFC reactor did not critically increase COD removal (Fig. 3).

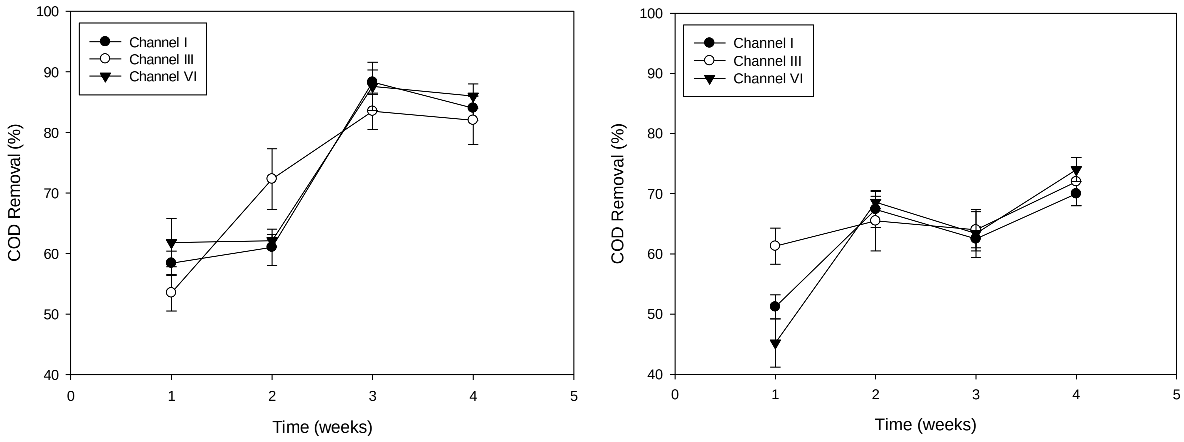

Figure 3. The COD removal efficieny curves of (a) the BPF-MFC; (b) the PF-MFC after 3 weeks of operational period.

CONCLUSION

Because of the current problems of conventional wastewater treatment systems, which are mainly high energy requirement and sludge disposal in the activated sludge systems, the promising concept of MFCs for wastewater treatment has recently emerged as an alternative wastewater treatment system. This study aimed to improve MFC efficiency using different types of reactors. In this context, two types of MFCs configuration which are BPF-MFC and PF-MFC operated to compare the performances. The results showed that BPF-MFC has better wastewater treatment performance than PF-MFC, and it indicates that reactor design is on of the key factor for improving MFC performance.

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