



Enhancement of Carbon Fiber Electrode Performance using Lactic Acid Bacteria and Steelmaking Slag

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Abstract Microbial fuel cell technology (MFCT) provides many benefits to rural regions, such as organic waste disposal and renewable energy recovery. However, its performance is low and must be improved for practical uses. Mixing steelmaking slag (SS) and lactic acid bacteria (LAB) with sediment can enhance the MFCT performance owing to LAB and iron ions dissolved from SS attaching to the electrode surface. This study proposes a simple method for attaching LAB and iron ions on carbon fiber electrode and subsequently evaluating its performance. A carbon fiber electrode was placed in a bottle containing tap water, SS, LAB, and bamboo powder (as nutrients for bacteria) for 7 days to allow LAB and iron ions to adhere to its surface. The electrode was then used as the cathode of MFCT. Results showed a decrease in the electrode potential and a consequent reduction in MFCT performance owing to the attached LAB and iron ions. The performance improved after the electrode was oxidized, suggesting that aeration is required during attachment to prevent the decrease in electrode potential. After 1 month of electricity generation, the electrode with the attachment produced high electrical current and exhibited low decrease in MFCT performance owing to electricity generation. Therefore, attaching LAB and iron ions on the electrode surface can improve the electrode performance and prevent performance degradation owing to electricity generation.

Keywords microbial fuel cell, performance, electrode potential, attachment, steelmaking slag, lactic acid bacteria

INTRODUCTION

Microbial fuel cell technology (MFCT) offers many benefits for rural regions, particularly in developing countries. For example, this method can be used to treat agricultural wastewater, household sewage, and organic waste, provide electricity to households, and recycle resources to farmlands (Touch et al., 2020). However, the performance of MFCT remains low and must be improved for practical uses. MFCT efficiency depends on the cathode and anode. A low electrode performance will restrain the overall performance of MFCT. According to Yamasaki et al. (2018), various types of potential losses occur during electron flow to an electrode. One of which is activation loss that strongly influences electrode performance. Activation loss should be minimized via pretreating the electrode to obtain a high MFCT performance. Furthermore, this loss increases during electricity generation owing to the crystallization of ions present in water on the electrode surface. Thus, a method for minimizing the performance reduction owing to electricity generation is necessary.

Adsorption of bacteria or metal ions on the electrode surface is a method for improving the electrode performance. Wang et al. (2009) successfully enhanced electrode performance by activating the bacteria at the electrode and consequently reducing potential losses. The boosted electrode performance through bacterial attachment and biofilm formation has been widely studied using the cyclic voltammetry measurement (Carmona-Martinez et al., 2011; Kang et al., 2012).

Electrode performance can also be improved via coating a catalyst on the electrode surface. Many types of catalyst have been used in chemical reactions, such as iron ions. Nishimura, et al. (2018) reported that ferric ions dissolved from steelmaking slag (SS) improve sediment microbial fuel cell (SMFC) performance. Using SS and lactic acid bacteria (LAB) in the anode of SMFC can also enhance its performance (Touch et al., 2020). On this basis, the attachment of iron ions and LAB on the electrode surface can increase the electrode performance.

OBJECTIVE

This study proposed a simple method for attaching LAB and iron ions dissolved from SS on carbon fiber electrode. Changes in electrode potential and electricity generation (electrode performance) owing to the attachment were subsequently investigated via measuring the polarization (current-voltage relation) of electrode to determine changes in potential loss and examining the current to detect alterations in MFCT performance when the electrode is used as the cathode. The effects of the attachment on MFCT performance reduction owing to electricity generation were also discussed.

METHODOLOGY

Experimental Materials and Procedures

Dip-coating and electrodeposition are used to attach metal oxides on an electrode surface. For practicality, a simple attachment process should be considered. Iron ions dissolved from SS are adsorbed on the cathode of MFCT during long-term electricity generation (more than 6 months). This study focuses on how to attach iron ions dissolved from SS to a carbon fiber electrode in a short span (1 week).

Cylindrical bottles (120-mm inner diameter and 150-mm height) were filled with 500-mL tap water. Some bottles contained 20-mm depth of SS and 20-mL lactic fermenting beverage, as shown in Fig. 1. Bamboo powder (5 g) was then added to the bottles and reduced the solution pH because of its fermentation. This process facilitates the dissolution of iron from SS. Furthermore, nutrients from bamboo powder can activate LAB. Therefore, iron ions and LAB can attach to the electrode surface in a short span.

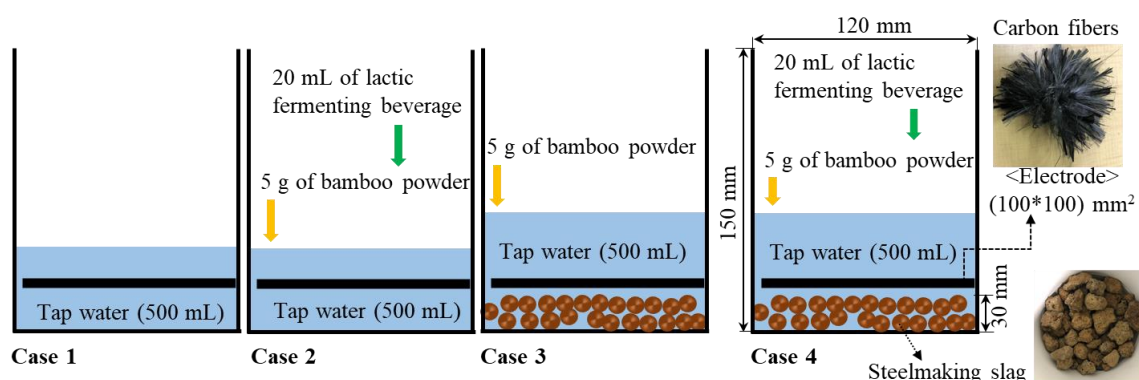


Fig. 1 Experimental devices and materials

The electrode material was carbon cloth (News Company, PL200-E), preheated at 500°C for 1 h to improve its performance (Nagatsu, et al. 2014). The heated carbon cloth with a 100-mm width and length was separated into fibers to form a brush-type electrode (photo in Fig. 1), which was then placed in the bottle for 7 days during bamboo powder fermentation.

Operations and Measurements

Experiments were conducted following the procedures in Fig. 2. The electrodes were placed in the solution for 7 days and then extracted from the bottle to measure their polarization using the circuit in Fig. 2a. In particular, the anode potential was fixed at -0.64 V to display a clear variation of the cathode (the electrode taken from the bottle) performance. An external resistance with $2.2\ \Omega$ – $10\ \text{k}\Omega$ was loaded between the anode and cathode. Cell voltage was recorded 1 min after loading each external resistance and used to calculate the current according to the Ohm’s law: $I = U/R_{\text{ex}}$, where U [V] is the voltage, I [A] is the current, and R_{ex} [Ω] is the external resistance. Power P was calculated according to $P = IU$. Current and power densities were obtained by dividing these values by the surface area of the electrode, i.e., $0.01\ \text{m}^2$.

After polarization measurements, the electrodes were placed in the bottle filled with tap water near the water surface for 7 days to examine the effects of oxidation on the electrode performance. The polarization of each electrode was remeasured after oxidation. The electrode was used as the cathode of SMFC (Fig. 2b) for 1-month electricity generation to examine its long-term performance. For electrical current generation, an external resistance of $2.2\ \Omega$ was loaded between the anode and cathode. Although different SMFCs were used for each case, the initial anode potential of each SMFC was the same order of magnitude.

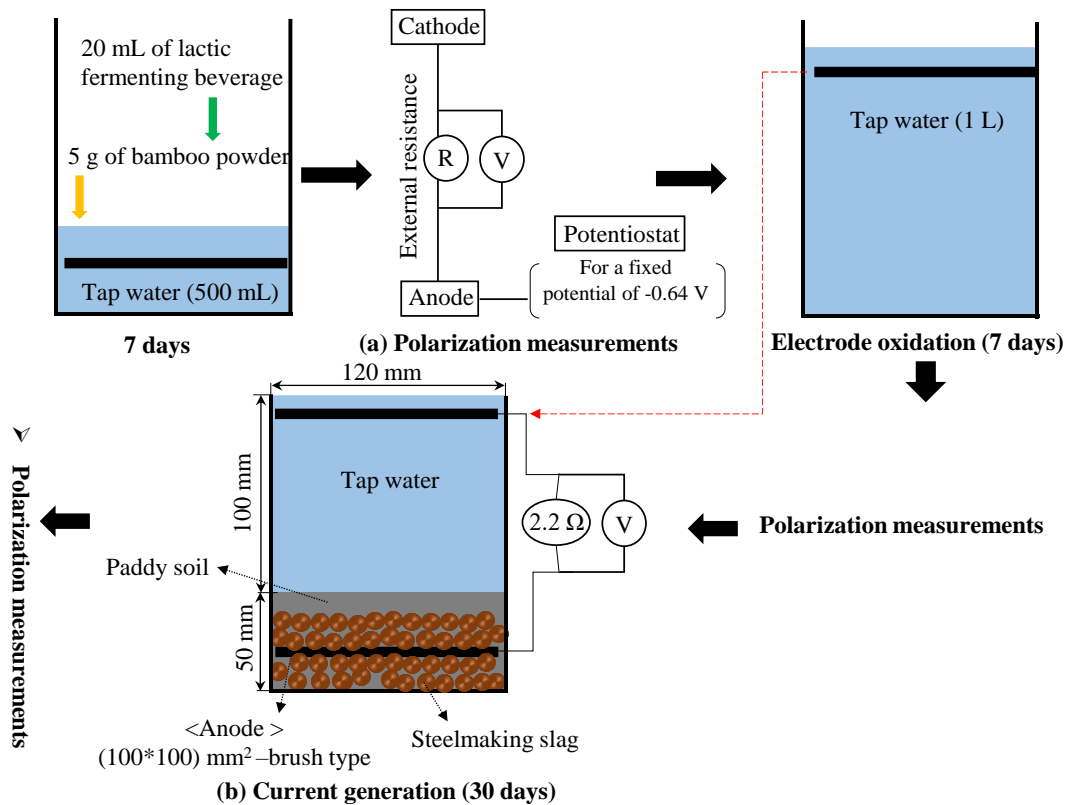


Fig. 2 Operations and measurement methods

After electricity generation, polarization and exchange current density were measured to examine the effects of electricity generation on the electrode performance. Exchange current density is an index for evaluating activation losses at the electrode surface, that is, a high exchange current indicates a small potential loss, i.e., a high electrode performance. Exchange current density was determined using the method noted in the study by Nagatsu et al. (2014).

RESULTS AND DISCUSSION

Effects of LAB and Iron Ion Attachment on the Electrode Performance

After fermentation and when each electrode was placed in tap water, the electrode potential was measured to examine the effects of LAB and iron ion attachment on the electrode performance. Comparison of electrode potential is shown in Fig. 3. The electrode potential largely decreased from 0.36 V (Case 1) to 0.01 V (Case 2) owing to LAB adsorption, to 0.06 V (Case 3) owing to iron ion adsorption, and to -0.11 V (Case 4) owing to LAB and iron ions adsorption (Fig. 3a). After the electrode was oxidized for 7 days (Fig. 3b), the electrode potential (Cases 2-4) largely increased (from 0.20 V to 0.25V).

These results indicate that the proposed method can attach LAB and iron ions dissolved from SS to the carbon fiber electrode. However, the attachment decreases the electrode potential. Consequently, the MFCT performance is reduced when the electrode is used immediately after the attachment. Given that electrode oxidation increases its potential, oxidizing the electrode with the attachment should be conducted before its usage in MFCT. Aeration should be performed during attachment to prevent the decrease in the electrode potential.

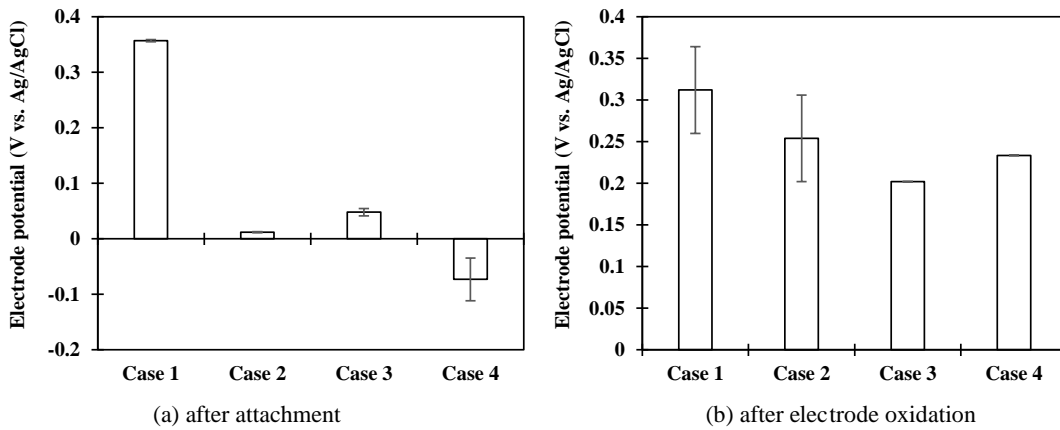


Fig. 3 Comparison of electrode potential at different conditions

Changes in Electrode Performance Owing to the Attachment of LAB and Iron Ions

Fig. 4 compares of the electrode performance of each condition. The electrode without attachment (Case 1) produced only approximately 3 mA/m² of current density. Meanwhile, the electrode attached to either LAB (Case 2) or iron ions (Case 3) generated 30–35 mA/m², a 10-fold increases (Fig. 4a). These results indicate the improved electrode performance can be attributed to the adsorption of LAB or iron ions on the electrode surface. A further increase in current density was also observed when LAB and iron ions were attached to the electrode (Fig. 4a, Case 4). Therefore, iron ions aid LAB to transfer electrons to electrode.

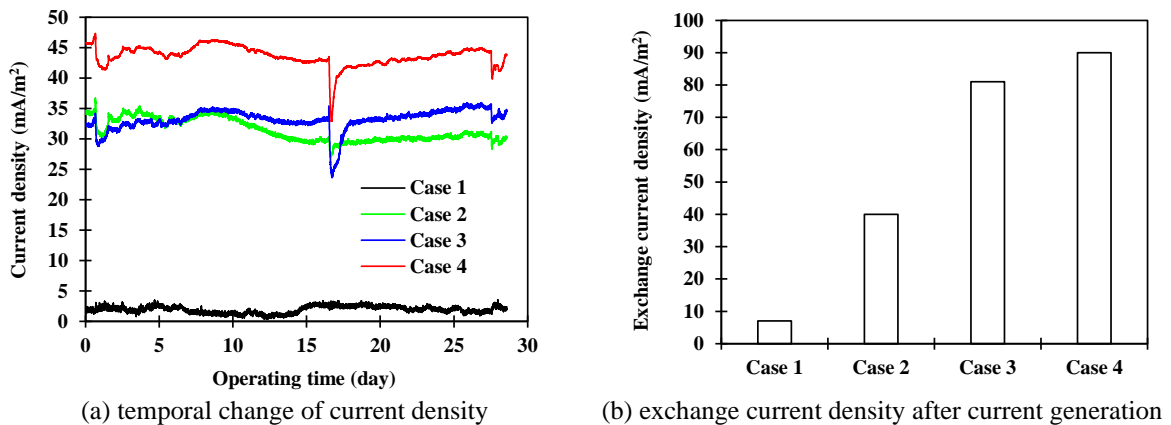


Fig. 4 Comparison of the electrode performance of each condition

The exchange current density of each case was compared in Fig. 4b. As shown in Fig. 4b, the exchange current density increased after the attachment of either LAB or iron ions on the electrode surface. This finding indicates that the potential loss at the electrode surface is reduced owing to the attachment, i.e., electrons are easily transferred to electrode via LAB or iron ions. In addition, the exchange current density of the electrode with iron ions attached (Case 3) was 80 mA/m² which was two-fold higher than that of the electrode with attached LAB (Case 2, 40 mA/m²). Iron ion attachment provides a better performance than LAB attachment. However, the combination of LAB and iron ions exhibits a higher performance than the use of each component alone.

Reducing the Performance Decrease Owing to Electricity Generation by LAB and Iron ions

Figures 5a and 5b depict the comparison of performance (current and power density relationship) for electrodes with and without electricity generation. Power density and current density decreased owing to electricity generation. In the experiments, crystallized compounds were observed on the electrode surface and can contribute to the decrease in performance.

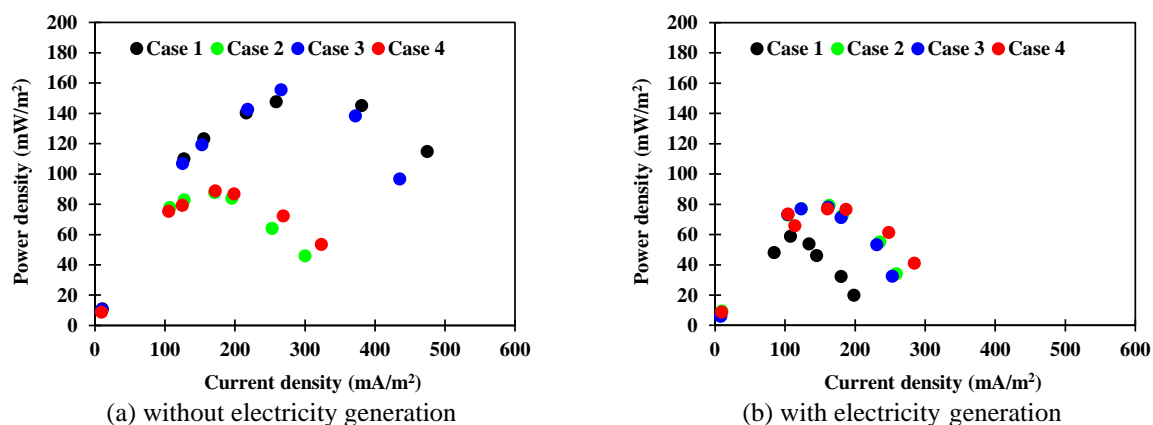


Fig. 5 Comparison of performance for electrodes with and without electricity generation

An 80-mW/m² reduction in power density was observed for the electrode without attachment (Case 1) and 70-mW/m² reduction for the electrode with iron ion attachment (Case 3). Only 12-mW/m² reduction in power density was observed when LAB attached to the electrode surface with and without iron ions (Cases 2 and 4). Therefore, LAB attachment on electrode surface effectively improves the reduced performance owing to electricity generation. Crystallization cannot occur on the electrode surface with LAB.

CONCLUSIONS

Laboratory experiments were conducted to verify the efficiency of the proposed simple method for attaching LAB and iron ions on a carbon fiber-electrode and to examine the effects of attachment on the electrode performance. Approximately 300-mV reduction in electrode potential was observed owing to the attachment. Nevertheless, the electrode potential recovered almost to the initial state after oxidizing the electrode by placing it in tap water near the water surface for 7 days. Thus, aeration should be conducted during attachment to prevent the decrease in the electrode potential. A 10-fold increase in current density was observed for the electrode attached with either LAB or iron ions. A high increase in current density was obtained when LAB and iron ions were attached to the electrode. On the basis of the increase in exchange current density owing to the attachment, the potential loss at the electrode surface is reduced owing to the attachment, i.e., electrons are easily transferred to electrode via LAB or iron ions. Finally, the performance decrease owing to electricity generation was largely (88%) reduced for the electrode attached to LAB. Therefore, the attachment of LAB on the electrode surface can restrain the formation of crystallized compounds.

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