A Novel Submersible Microbial Fuel Cell with Bubble-retaining Cover for Long-term Power Generation

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***Abstract*—This study proposes a novel Flooded Microbial Fuel Cell (FMFC). Conventional Microbial Fuel Cells (MFCs) require the cathode to be exposed to air, which limits their installation to locations near the water surface. Flooded MFCs suffer from oxygen supply deficiencies and biofouling, leading to rapid performance degradation. Therefore, this study employs a cobalt-copper conductive material with bactericidal properties for the cathode. Additionally, an umbrella-shaped cover that traps bubbles is mounted over the cathode, creating a structure that maintains oxygen supply even underwater. As a result, the covered configuration showed significantly improved power generation sustainability compared to the uncovered configuration. Notably, when using cobalt material, stable power generation lasting over three months was confirmed. This FMFC can be installed in deep environments not in contact with the water surface, such as aeration tanks in water purification plants or rivers, where oxygen bubbles are abundant in the liquid. It achieves both long-term power generation sustainability and installation flexibility.**

***Keywords*—flooded MFCs, cobalt, copper, power generation sustainability, umbrella-shaped cover, biofouling prevention, aeration tank application**

I. Introduction

In today's world, where global warming is progressing and the depletion of fossil fuel resources is becoming more serious, it is becoming increasingly important to secure sustainable energy sources while reducing the environmental burden [1]. Although renewable energy technologies such as solar power and wind power have already been introduced in various aspects of society and industry, there are limits to their ability to provide a stable power supply because they are dependent on weather and location conditions [2]. Therefore, there is a need to develop new technologies that can supply power sustainably at low cost, independent of weather and geographical conditions. In recent years, Microbial Fuel Cells (MFCs) have attracted attention as a technology that can meet these needs [3].

Microbial Fuel Cell (MFC) technology utilizes electrons released during the decomposition of organic matter by electricity-producing microorganisms (e.g., Shewanella, Geobacter) inhabiting rivers, soil, and wastewater to convert chemical energy into electrical energy [4]. Specifically, electricity is generated by exploiting the potential difference between two electrodes: the anode and the cathode [5]. At the anode, microorganisms oxidize organic matter, releasing electrons and protons. The electrons flow through an external circuit to the cathode, where they are transferred to acceptors such as oxygen, driving redox reactions. This continuous electron transfer maintains the potential difference, resulting in a current in the external circuit and enabling electricity generation. MFCs offer relatively low-cost power generation while simultaneously providing wastewater treatment benefits [6]. This dual function makes MFCs a highly promising technology for simultaneously achieving environmental conservation and energy production [7].

Especially in water bodies such as rivers, lakes, and sewage treatment facilities, where oxygen is abundant, the low-cost and sustainable power generation capability of MFC is expected to be used to drive remote sensors, IoT devices, and environmental monitoring equipment [8]. However, to realize these applications, it is essential for MFCs to provide a stable power supply over a wide area and for an extended period, not just for local installations.

Two types of structures are only representative examples of current MFCs. One is a floating MFC, in which part of the cathode is exposed to the air. This type of MFC can efficiently utilize oxygen in the air and, under ideal conditions, can generate stable power for a long period of time [9]. However, because installation is limited to the vicinity of the water surface, the range of possible power generation is narrow, and there are restrictions on wide-scale deployment [10]. The other is the submersible MFC, in which the entire electrode is installed in water, and catalytic materials are used to promote the oxygen reduction reaction. The submersible type can be used over a wide area because it can be installed over the entire water column, but the problem is that the cathode is always in the water, resulting in insufficient oxygen supply, which accelerates biofilm formation and electrode degradation, and maintenance is usually required about every month [11–12].

Various solutions have been proposed, including improvement of the oxygen reduction catalyst, surface coating to inhibit biofilm formation, and adoption of partially exposed structures and air diffusion membranes. However, all these methods involve increased cost and structural complexity, and their practical application in wide-range and deep-water environments remains limited [13].

Therefore, this study aims to develop a new MFC structure that simultaneously overcomes the problems of conventional floating and submerged MFCs and enables stable operation over a wide area and for a long period of time. Specifically, we propose a cathode structure that can sustainably maintain oxygen supply even in flooded conditions. The cathode is made of a material that has excellent electrical conductivity and inhibits excessive microbial growth and is equipped with an umbrella-like cover that efficiently holds oxygen, thereby locally collecting oxygen and increasing the oxygen concentration on the electrode surface. This structure is expected to suppress biofilm formation and electrode

degradation and maintain stable power generation over the long term, even in flooded environments. Furthermore, this design can be applied to a wide range of oxygen supply environments, such as rivers, lakes, and aeration tanks in water purification plants, and can significantly improve the installation restrictions and maintenance frequency problems faced by conventional MFCs. The results of this research are expected to advance the social implementation of MFC and contribute to the sustainable drive of remote monitoring and Internet of Things (IoT) devices, as well as to the advancement of water quality management and environmental monitoring.

II. Materials and Methods

A. Anode Electrode Preparation Process

The anode material is Rice Husk Charcoal (RHC) carbonized by the smoke method widely practiced by farmers at the Tokorozawa Planting Bee Center (Saitama, Japan). The smoke method is a traditional method of gradually carbonizing rice husks without applying high temperatures. The resulting RHC was subjected to chemical etching by agitation in an aqueous NaOH solution for 30 min. This is expected to improve conductivity and surface reactivity. Next, 1.8 g of etched RHC powder per anode was mixed with 7 mL of commercial black ink (Kuretake Co. Ltd, Nara, Japan) to form a uniform paste. The mixture was poured into a 2 cm × 2 cm × 1 cm plastic mold, and a hard stainless mesh (SSM, 304-100 mesh) was inserted in the center as a conductive auxiliary material. The samples were dried and cured at room temperature for approximately 24 h and used as the final anode electrode. A total of four were fabricated for use in control experiments, as shown in Fig. 1. In addition, each anode was immersed in soil (collected from a vacant lot on the Biwako-Kusatsu campus of Ritsumeikan University) for approximately one week to allow biofilm formation on the surface of the resulting anode electrode. During the immersion period, the soil was maintained under room temperature conditions, and the moisture in the soil was maintained as appropriate to ensure the survival and growth of microorganisms. This process resulted in the formation of a uniform and sufficiently thick biofilm on each anode surface.

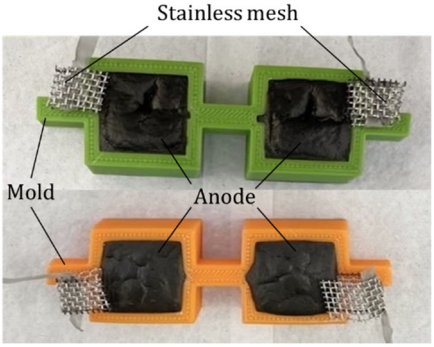

Fig. 1. Photograph of the anode.

B. Copper and Cobalt Cathode Preparations

To effectively suppress biofilm formation on the cathode, two different cathode materials, copper and cobalt, were selected and used [14].

Copper cathodes were prepared using the following procedure. For electrode molding, a T-shaped plastic mold with a volume of 4.5 cm^3 was used. First, 1 g of copper powder was measured and added to 30 mL of commercially available ink to form a suspension. This mixture was stirred at 800 rpm for 3 h using a magnetic stirrer to prepare a uniform copper ink. For each cathode, 6.75 mL of copper ink was taken, and 1.35 g of RHC was added and stirred thoroughly. The prepared mixture was injected into the mold, and a hard stainless mesh was inserted in the center as a conductive auxiliary material, like the anode. The mixture was left to dry at room temperature for 24 h, resulting in a copper cathode as shown in Fig. 2 (a). Flexible stainless mesh (#400φ0.03, CLEVER, Aichi, Japan) was used to connect the anode and cathode by contacting them with the hard stainless mesh.

For the cobalt cathode, first, 1.58 g of potassium permanganate was added to 100 mL of purified water, and the mixture was stirred at 400 rpm for 30 min using a magnetic stirrer. The resulting solution was mixed with 135.6 mL of cobalt (II) nitrate hexahydrate solution (2.83% concentration) and stirred at 400 rpm and 70 °C for 30 min. Then, 1.0 g of carbon black was added and mixed, and the mixture was dried at 60 °C for 24 h to obtain cobalt powder. For the preparation of each cathode, 0.84 g of cobalt powder, 3.66 mL of ink, and 0.6 g of RHC were mixed and injected into a T-shaped plastic mold, similar to the one used for the copper cathode, with a hard stainless mesh inserted in the center. The mixture was left to dry at room temperature for 24 h, resulting in a cobalt cathode as shown in Fig. 2(b). Flexible stainless mesh was used to connect the anode and cathode by bringing them into contact with the hard stainless mesh.

Four cathodes were created for the comparative experiment. As shown in Fig. 2, one plastic cover was attached to each cathode, while the other was left uncovered for the experiment. This allowed for a clear comparison of the effect of the cover on the experimental results.

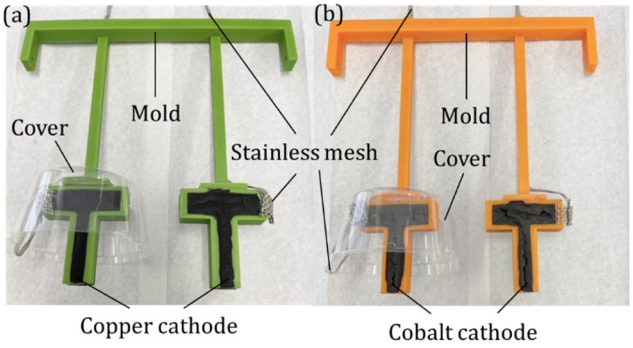

Fig. 2. Photograph, (a) the copper cathodes, (b) the cobalt cathodes.

C. Covered Cathode Creation Method

A plastic umbrella-shaped cover was attached to part of the cathode and installed on the upper portion of the electrode, as shown in Fig. 3. This cover was designed to partially enclose the space above the electrode in an umbrella shape rather than covering the entire electrode surface. The umbrella cover was fabricated from a durable, water-resistant plastic material.

Furthermore, as shown in Fig. 4, the electrode configuration was adjusted so that bubbles generated by

aeration flowed into the umbrella cover. As a result, air was temporarily retained inside the cover, allowing part of the cathode surface to directly contact air while remaining submerged in water. The cathode was shaped into a T-type configuration to increase the portion of its surface area exposed to air within the cover relative to the total cathode surface. This design also aims to prevent liquid from penetrating across the entire cathode surface and suppress the formation of a biofilm over the whole cathode. This structure enables a more efficient oxygen supply compared to a conventional fully submerged cathode and is considered to promote oxygen reduction reactions.

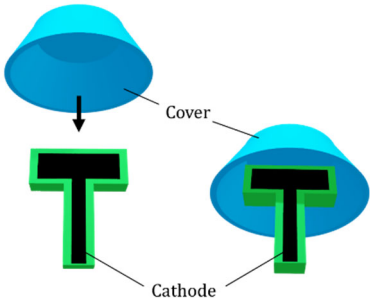

Fig. 3. Covered cathode structure.

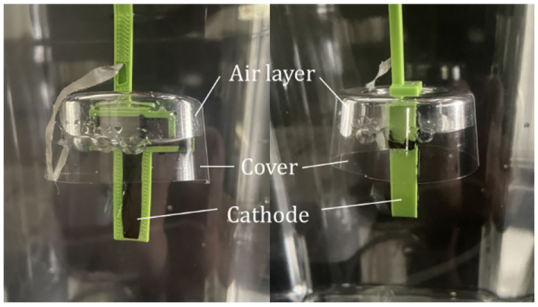

Fig. 4. Air accumulation inside the cover.

The experiment was conducted by installing both the umbrella cathode and the uncovered cathode in the same container under identical conditions, thereby enabling a clear evaluation of the structural effect attributable to the presence or absence of the cover.

D. Experimental Setup

In this study, Lysogeny Broth (LB) medium was added sequentially to maintain the Chemical Oxygen Demand (COD) at 650 ± 50 mg/L. In addition, an aeration device (Zhongshan Ibay Electric Appliance Co., Ltd) was used to continuously supply oxygen so that the Dissolved Oxygen (DO) concentration was maintained at 2–6 mg/L. These conditions simulate the oxygen supply environment in a water treatment plant aeration tank.

As shown in Fig. 5, two cathodes and two anodes were installed in the same container as one set. Two types of cathodes, with and without covers, were used for a comparative experiment. This setup was applied to both copper and cobalt cathodes to compare electrode behavior under identical conditions.

Furthermore, one anode was paired with each cathode, forming one electrode pair. This enabled simultaneous observation of multiple electrode reactions within the same vessel, allowing for a clear evaluation of differences in structural effects.

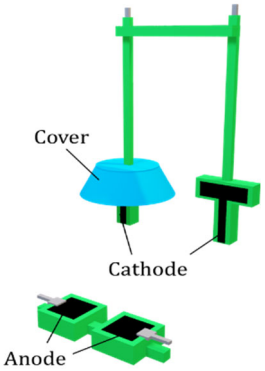

Fig. 5. Electrode setup diagram.

E. Lysogeny Broth (LB) Medium Creation

Lysogeny Broth (LB) medium was prepared for use as the culture medium. Specifically, 5.0 g of tryptone as a nitrogen source and carbon source, 2.5 g of yeast extract to supply vitamins and growth factors, and 5.0 g of sodium chloride were weighed out and added sequentially to 500 mL of purified water, ensuring complete dissolution. Furthermore, to adjust the medium's pH to the appropriate range, 2.5 mL of sodium hydroxide solution (approximately 1.23% concentration) was added. The prepared solution was then sterilized by autoclaving (121 °C, 30 min) to completely remove microorganisms and unwanted contaminants. The resulting sterile LB medium was diluted 25-fold with water and adjusted to a COD of 650 ± 50 mg/L for use in the experiment.

F. Measurement method

COD measurements were performed using a dichromate reagent (TNT822, Hach) and a spectrophotometer (DR3900, Hach). Dissolved Oxygen (DO) concentration was measured using a dissolved oxygen meter (Slyfox). The voltage between the anode and cathode was measured using a 10 kΩ external resistor and a digital multimeter (NT8233D PRO, Neoteck).

The potential of each electrode was evaluated using an Ag/AgCl reference electrode. The Ag/AgCl reference electrode (hereafter referred to as the AgCl rod) was fabricated by forming a silver chloride (AgCl) layer on the surface of a pure silver rod (Ag), thereby imparting electrochemical properties suitable for use as a reference electrode. The AgCl rod was used to measure the potential of the anode and cathode, allowing for a quantitative evaluation of the electrode reaction behavior and power generation performance.

Using a resistance selector (RM-7, MCP JAPAN), the external resistance was varied stepwise in the range of 400 Ω to 10 kΩ. The corresponding steady-state voltage was measured with a digital multimeter (MS8233D, Crenova). Based on the measured voltage V (mV) and resistance R (Ω), the output power P (μW) was calculated according to Eq. (1). In addition, the calculated power was normalized by the effective surface area of the electrode to determine the power density.

$$P = V^2/R \tag{1}$$

AgCl measurements were taken approximately every other day, and power measurements were taken approximately every five days.

III. Results and Discussion

A. Ag/AgCl Measurement on Copper Cathodes

Fig. 6 shows the Ag/AgCl measurement results for the copper cathode with Fig. 6(a) a cover and without Fig. 6(b) a cover. The orange line indicates the cathode measurement results, while the blue line indicates the anode measurement results. Throughout the experiment, COD was maintained at 650 ± 50 mg/L by adjusting the supply according to LB consumption. After day 20, the anode potential was observed to stabilize.

In graph Fig. 6(b), using the uncovered cathode, the cathode potential began to decline around day 20, and power generation completely ceased by day 36. This phenomenon is likely associated with degradation of the cathode surface and subsequent biofilm adhesion. Moreover, the cathode was more directly affected by external oxygen and impurities, which likely led to rapid inhibition of the reaction sites and performance degradation.

In contrast, the graph for the covered cathode, Fig. 6(a), showed relatively stable performance until day 30, after which a decreasing trend in cathode potential was observed. This suggests that the cover suppresses degradation progression to some extent, thereby improving the sustainability of power generation. Specifically, the cover likely mitigated the impact of external environmental factors, maintaining stability at the reaction interface. Therefore, protecting the cathode surface is considered crucial for ensuring the long-term stability of power generation.

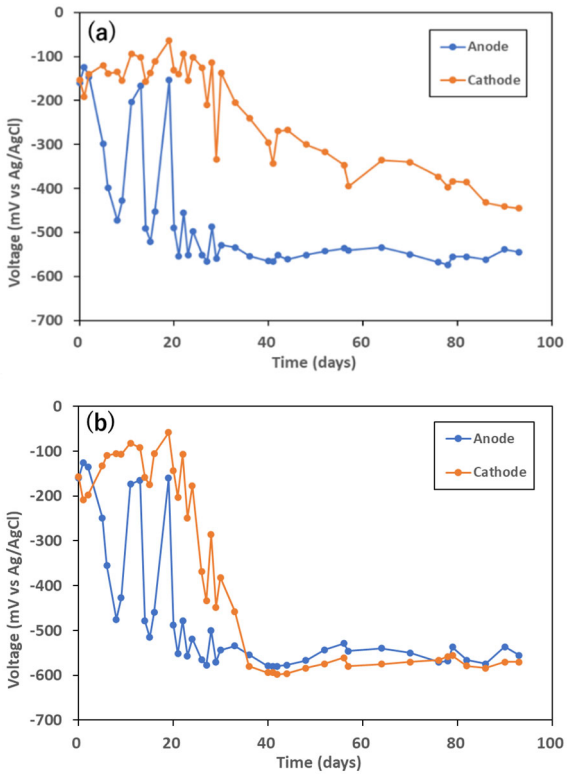

Fig. 6. Ag/AgCl measurement on copper cathode (a) with cover, (b) without cover.

B. Ag/AgCl Measurement in Cobalt Cathodes

Fig. 7 shows the Ag/AgCl measurement results for the cobalt cathode, with Fig. 7(a) showing the results with a cover and Fig. 7(b) showing the results without a cover. As in Fig. 6, the orange line indicates the cathode measurement results, while the blue line indicates the anode measurement results.

In Fig. 7(b), the cathode potential gradually decreased from the first day of the experiment, reaching a value nearly identical to the anode around day 70, indicating that power generation had ceased. This behavior is like that observed in Fig. 6(b) and is likely caused by degradation of the cathode surface. On the other hand, Fig. 7(a) shows that the potential remained stable even after 90 days of experimentation, demonstrating that the protective cover preserves the cathode surface and enhances the sustainability of power generation. Comparison between Fig. 7(a) and (b) confirms a clear difference in the long-term power generation stability depending on the presence of a cover.

Figs. 6 and 7 clearly show a distinct difference in the long-term power generation stability of the cathode depending on the presence or absence of a cover. This demonstrates the effectiveness of the cover regardless of the cathode material, indicating that the improvement in oxygen supply is attributable not to the intrinsic properties of the electrode, but to the cover structure itself. These results suggest that the proposed cover design is versatile and can potentially enhance the long-term performance of various cathode materials in FMFCs.

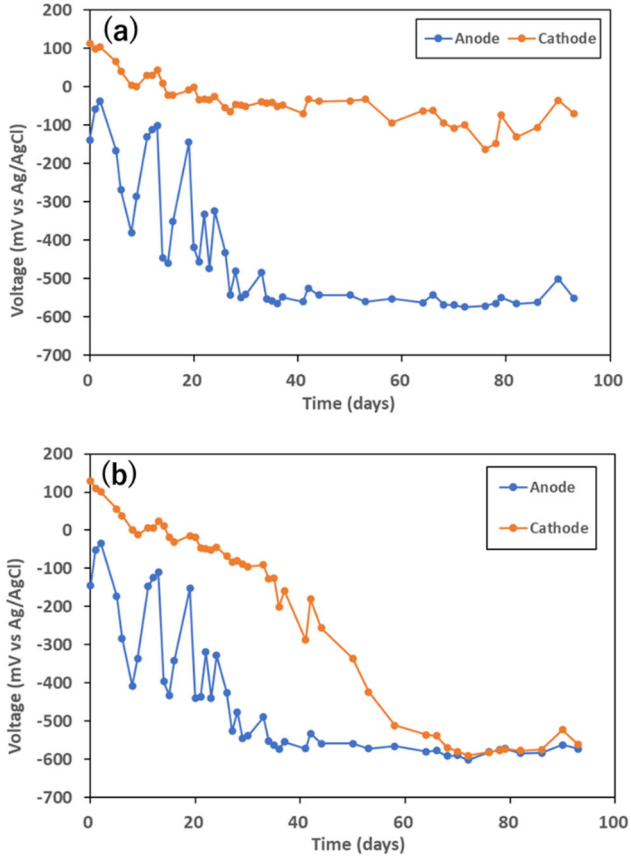

Fig. 7. Ag/AgCl measurement on cobalt cathode (a) with cover, (b) without cover.

C. Maximum Power Density over Time

Fig. 8 shows the temporal changes in maximum power density for four conditions: copper cathodes (with/without cover) and cobalt cathodes (with/without cover). In this experiment, power measurements were initiated after the 26th day, when the anode potential had stabilized.

For the uncovered copper cathode, the maximum power density dropped to zero approximately 35 days after the start of measurement. In contrast, the covered copper cathode exhibited a gradual decline over time but continued generating power even after 90 days. The uncovered cobalt cathode also showed a sharp decrease, reaching zero around 65 days. In contrast, the covered cobalt cathode maintained power generation for over 90 days, with no significant change in power density.

These results indicate that cathodes with covers can sustain higher power levels than uncovered cathodes over the long term, even at maximum power density, clearly demonstrating the effectiveness of the cover. Moreover, this enhanced durability suggests the potential to extend maintenance intervals for FMFCs.

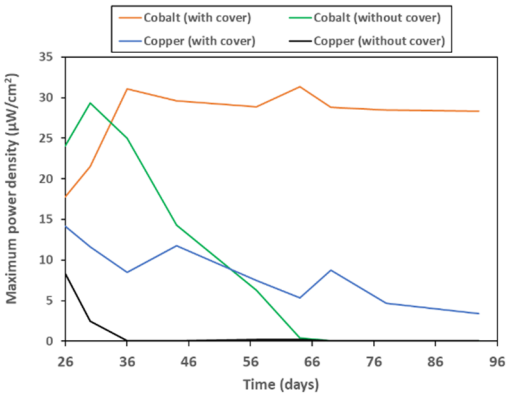

Fig. 8. Transition of maximum power density over time.

IV. Conclusion

This study compared the power generation performance of FMFCs with and without covers using copper and cobalt cathodes. Covered cathodes, compared to uncovered ones, maintained higher power output over extended periods, demonstrating improved power generation sustainability through stabilized oxygen supply and protection of the cathode surface. Notably, the effectiveness of the cover was confirmed to be independent of the cathode material, with stable power generation maintained for over 90 days in the cobalt cathode. These results indicate that the proposed cover design is versatile and has the potential to enhance the long-term performance of various cathode materials in FMFCs. Furthermore, this covered FMFC contributes to long-term power generation maintenance and has the potential to extend maintenance intervals. As a submersible system, it is not limited to installation on water surfaces and is expected to be suitable for practical applications in various aquatic environments, such as water purification plants and rivers.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Kozo Taguchi conceptualized the research. Tomoya Yabuzaki analyzed the data. Tomoya Yabuzaki and Trang Nakamoto wrote the paper, and all authors approved the final version.

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