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Distributed multiple-anodes benthic microbial fuel cell as reliable power source for subsea sensors

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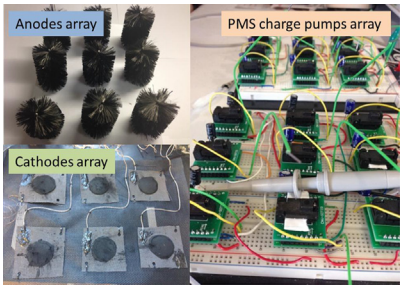
HIGHLIGHTS

- Multiple-anodes/cathode of DBMFCs has high stability and robustness under bioturbation.
- Multiple-charge pumps in PMS enhance the energy delivery efficiency.
- Power output of DBMFCs is closely associated with nutrient contents in sediment.
- The entity of DBMFC/PMS/sensors well represents the stable power output in subsea.

GRAPHICAL ABSTRACT



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ABSTRACT

A new type distributed benthic microbial fuel cell (MFC) (DBMFC) consisting of 18 MFC arrays was developed to enhance the robustness and stability of the power source for subsea sensor networks. A power management system (PMS) was integrated into the DBMFC system to boost the power output for two temperature sensors. The PMS was specifically designed with 18 charge pumps capable of simultaneously harvesting energy from 6 MFC units (18 anodes total) in the DBMFC system. The pilot scale DBMFC (total sediment volume: 1 m^3) with continuous ocean water supply showed that the power outputs of individual MFC units were affected by the organic carbon and nitrogen contents in the sediment pore water. The MFC units with higher power output resulted in faster charging/discharging rate of the PMS supercapacitor. Manual disconnection of anodes from the PMS was conducted to simulate the anode malfunction caused by bioturbation. Fewer functional anodes (e.g. 12 out of 18 anodes were disconnected) slowed the charging/discharging rate of the PMS supercapacitor but still supported the PMS to regularly power two sensors. This scale-up DBMFC/PMS/sensor study demonstrated that multiple MFC units with multiple PMS substantially enhanced the stability and robustness of power supply to subsea sensors.

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1. Introduction

A microbial fuel cell (MFC) is a bioelectrochemical system capable of producing bioelectricity from organic substrates (e.g. carbohydrate, protein, and fatty acid) [1–3]. The electrons

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generated by anaerobic electrogenic bacteria on the anode surface are transferred through an external circuit to the cathode, where oxygen is reduced and combined with protons to form water [4]. MFC systems pose a great potential for organic removal and sustainable power generation. In recent years, benthic (sediment) MFCs (BMFCs) have been developed by embedding anodes into the sediment rich in organic nutrients and microorganisms and floating cathodes atop ocean water rich in oxygen. The oxidation reduction potential (ORP) difference between sediment and ocean water is the driven force for the power generation in BMFCs [5].

Since the first prototypical BMFC was developed in 2002 [6], much effort has been invested into making BMFCs a long–term power source for subsea sensing devices (e.g. environmental monitoring, pollution detection, and security surveillance) [7–11]. Power generation (0.74 mW m^{-3}—16 mW m^{-3}) of BMFCs has been enhanced by fabricating electrochemically active electrode materials [9,12,13], developing compact BMFC configuration [11], and increasing electrode area [8]. Currently, there are two major issues associated with BMFCs performance. The first is the stability of BMFC operation in the dynamic ocean environment. Bioturbation caused by the penetration of aquatic organisms and marine currents could seep oxygen into sediment and disturb anaerobic anode environment [14,15]. Until now, most of the BMFCs consisted of a chamber with a single anode and cathode pairing [7–10], which become vulnerable or even stop producing electricity under bioturbation, thus hindering the stability and reliability as a power source for subsea sensors. In order to increase stability, a novel BMFC configuration, distributed BMFCs (DBMFCs) with multi–anode associated with a single cathode were developed, which showed high stability under bioturbation [16]. When one anode is impaired, other anodes can still provide stable electron transport for consistent power generation. The lab–scale batch tests (0.1 m^3) proved that the multiple–anode configuration greatly improved the power generation compared with BMFCs with single anode/cathode, and provided sufficient power output even as several anodes were impaired.

The second issue is that MFCs have inherent low voltage output (less than 0.8 V) caused by energy loss and bacterial metabolic loss [4,7], while most of subsea sensors require 1.3–7 V or ~2.5 W [7,8,10,17]. Power management system (PMS) has been developed to connect BMFCs with sensors and boost the power output of BMFCs [7,8,10,17,18]. A PMS usually contains a capacitor to store energy, and a charge pump/DC–DC converter to boost the voltage [7,17,18]. For BMFCs with single anode/cathode configuration, the anode/cathode malfunction could easily cause the PMS disruption. On the contrary, for BMFCs with multiple anodes/cathodes, the inefficiency or malfunction of individual anode/cathode will not cause a complete shutdown of PMS, since other functional arrays of anodes/cathodes can still charge the PMS. But the malfunction of anodes could cause a longer charging period of the capacitor.

Based on the success of the lab-scale batch-mode DBMFC tests with 9 arrays of anodes and cathodes (Sediment volume: 0.1 m^3) [16], this study has been transitioned to enhancing the stability and robustness of the scale-up DBMFC system (volume: 1.0 m^3) by tripling electrode array numbers, developing the integrated entity consisting of DBMFC, PMS, and sensors, and operating in the continuous flow mode with real ocean water and sediment taken from the Long Island Sound (LIS). With the integration of a PMS developed specifically for multiple-MFC configuration, the DBMFC was expected to effectively reduce the impact of bioturbation or anode malfunction, and provide durable and reliable power generation to support sensors in benthic environment. The stability of this integrated system was extensively examined under adverse conditions (e.g simulated bioturbation). The correlation of power output of individual MFC units with nutrient contents in sediment was established.

2. Materials and methods

2.1. DBMFC configuration and operations

The DBMFC was deployed in a fiber glass tank (size: 183 × 91 × 61 cm, total volume: 1 m^3), and fed with coastal sediment and ocean water (sediment volume and depth: 0.40 m^3 and 24 cm; water phase volume and depth: 0.25 m^3 and 15 cm) acquired from the LIS (Avery Point, USA). The ocean water was continuously pumped to the tank through an inlet and discharged through an outlet, in order to keep the ocean water in the tank fresh and maintain sufficient oxygen in ocean water. The DBMFC was configured with 18 MFC units, each having 1 cathode and 3 anodes being connected in parallel (totally 18 cathodes and 54 anodes) (Fig. 1A and B). The anodes were made of carbon brush, each with an overall length of 12.7 cm, bristle section length of 7.62 cm and bristle diameter of 5.08 cm (Fig. 1C). The anodes were vertically inserted towards the bottom of the sediment and were evenly distributed within the tank (Fig. 1A). The effective volume of the individual anode was assumed as half the volume of the bristle section, since the carbon brush shrunk in the sediment. The cathodes were made of carbon cloth with activated carbon (effective area: the area of activated carbon, 6.25 cm^2) binding on the surface with Polytetrafluoroethylene (PTFE) [19] (Fig. 1D) and were distributed evenly on the water surface. Anodes, cathodes, and PMS were connected using water proofed copper wires.

2.2. Power management system

A power management system (PMS) was integrated with the DBMFC system in order to boost the power output for a device with the voltage requirement of 3.3 V that includes two temperature sensors (Fig. 1A). Unlike the PMS for the BMFCs with single anode/cathode, the PMS used in this study was designed with 18 charge pumps (Fig. 1E) capable of simultaneously harvesting the charge from 6 MFC units (with 18 anodes totally) in the DBMFC system. Each charge pump with a 450 μF capacitor (S-882Z, Seiko Instruments Inc.) was connected to a dedicated anode while a cluster of three charge pumps shared one cathode. The charge pump array was further connected to a supercapacitor (1.22 F) that stored the accumulated power when a charge pump reached its discharge-start value. The supercapacitor supported two temperature sensors (MadgeTech RFTC4000A) to transmit readings.

A switching circuit, using a series of ultra-low threshold N-channel metal–oxide–semiconductor field-effect transistor (N-MOSFET) and P-channel metal–oxide–semiconductor field-effect transistor (P-MOSFET) transistors to minimize power consumption of the PMS, was turned on once the supercapacitor reached a threshold defined by the circuit (~1.33 V), and powered the boost converter that was configured to output 3.3 V to two temperature sensors. The boost converter operated at the voltages above 0.8 V. Once the supercapacitor voltage dropped to 0.8 V, the switch turned off, and the charge pumps resumed the charging stage.

2.3. Measurements and chemical analysis

An external resistance ($R_{ext.}$) of 1000 Ω was applied to all MFC units except the ones that were directly connected with the PMS. Voltage generation (V) over the R_{ext} was recorded every 2 h using a Keithley data logging system. During the test, two groups of MFC units, with one group consisting of 6 MFC units (18 anodes being connected with 6 cathodes) with each MFC power output higher