Energy Extraction from a Large-scale Microbial Fuel Cell System Treating Municipal Wastewater

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Abstract

Development of microbial fuel cell (MFC) technology must address the challenges associated with energy extraction from large-scale MFC systems consisting of multiple modules. Herein, energy extraction is investigated with a 200-L MFC system (effective volume of 100 L for this study) treating actual municipal wastewater. A commercially available energy harvesting device (BQ 25504) is used successfully to convert 0.8-2.4 V from the MFCs to 5V for charging ultracapacitors and running a DC motor. Four different types of serial connection containing different numbers of MFC modules are examined for energy extraction and conversion efficiency. The connection containing three rows of the MFCs has exhibited the best performance with the highest power output of ~114 mW and the conversion efficiency of ~80%. The weak performance of one-row MFCs negatively affects the overall performance of the connected MFCs in terms of both energy production and conversion. Those results indicate that an MFC system with balanced performance among individual modules will be critical to energy extraction. Future work will focus on application of the extracted energy to support MFC operation.

Keywords: Microbial fuel cells; energy harvesting; maximum power point tracking; charging; wastewater.

1. Introduction

Microbial fuel cells (MFCs) have been intensively studied as an emerging technology for sustainable wastewater treatment with bioenergy recovery. Through interaction between microorganisms and solid electron acceptors/donors, MFCs can directly generate electricity from oxidation of organic contaminants [1, 2]. With advancement of this technology in various aspects such as microbiology and materials, a key question arises: how to extract and apply the produced energy. While most studies only report the performance of electricity generation in MFCs, some have investigated energy extraction and application to power small electronics such as wireless sensors [3-6] or charge batteries and capacitors [7-12]. It has been realized that the difficulty of utilizing energy from MFCs is mainly due to the relatively low power and voltage output, which would limit efficiency and application for powering electronics by using commercial power conversion circuits.

Several customized energy harvesting systems have been developed for MFCs applications, such as the ones based on capacitor, charge pump, and boost converter, to increase the output voltage and power output efficiency [7, 8, 12, 13]. However, due to the limitation of the size of single MFC and the number of MFCs in one system, the studies of energy harvesting are still focusing on small-load applications because the output energy is too small to drive electronics with high-power requirement. The electric devices such as DC motors (pumps) with a demand for amp-level current and high voltage input (>5 V) are rarely investigated in the MFC studies except a recent study of a 90 L-scale MFC treating brewery wastewater that a 3-6 V DC pump was successfully used as to feed solution, powered by electricity generated by the MFC [14].

Clearly, more studies with the MFCs at large scale (>50 L) treating actual wastewater should be conducted for further understanding of the system (and its limitation).

To extract energy from MFCs, maximum power point tracking (MPPT) could be an efficient strategy, which optimizes the power output by tracking the maximum power voltage (MPV) of power sources (e.g., MFCs). The purpose of MPPT is to reduce the power loss by matching the load impedance dynamically [7], and it has been adapted with different algorithms such as perturb and observe (P&O) [15, 16], partial open circuit voltage (OCV) tracking [7, 17], and multiunit optimization [18] [16, 19] for MFCs applications. The system without MPPT could have 50% loss of output power while the voltage reversal might also be avoided by applying MPPT devices for each cell in one system [18, 20].

Although multiple high-efficiency energy harvesting devices have been developed for single MFC with low voltage input, they have not been well investigated for an MFC system consisting of multiple modules at a large scale treating actual wastewater, and it is not clear whether one EHS per MFC module would work in a multiple-module MFC system and associated energy loss and maintenance/operation issues. In addition, most of the prior studies were based on bench-scale systems treating synthetic organic solution, or sediment-type MFCs [21], and very few of them had MFC systems treating actual wastewater and/or at a large scale (e.g., > 50 L). In this study, energy production and conversion efficiency from a large-scale MFC system treating actual municipal wastewater (installed in a local wastewater treatment plant) was evaluated through parallel and serial electrical connection of 48 MFC modules (total anode volume of ~

100 L) by using a commercially available device TI BQ 25504 with MPPT using a partial OCV method. Because the efficiency of an EHS may vary as the input of voltage and current fluctuates due to the changes of operation and environmental conditions, it is necessary to examine the final power output, MPPT function, and conversion efficiency when actual wastewater is used as a substrate and multiple MFC modules are involved in one system. The performance of energy extraction from multiple connections with various voltage input ranging from 0.8 to 2.4 V (OCV) were examined as well to determine the optimized electrical connection of MFCs for energy conversion. It should be noted that the present paper focuses on energy extraction with brief introduction of the performance of this MFC system, and its long-term treatment performance will be reported in a separate publication.

2. Materials and Methods

2.1. The MFC system

The MFC system consisted of 96 2-L tubular MFCs constructed by using the method described in a previous study [22], except that the cathode catalyst was nitrogen-doped activated carbon prepared by using urea as a nitrogen source. The 96 MFCs were placed as 12 x 8 array with 12 MFCs in each row and 8 rows in total (R1-8) (Fig. S1). The 8 rows were divided into four groups, with 2 rows in each group that had 24 MFCs hydraulically connected through plug-flow feeding. However, only 48 cells (four rows, R1, 3, 5, and 7) were used for this study. The MFC system was started by feeding the effluent from a primary clarifier (Peppers Ferry wastewater treatment plant, Radford, VA, USA) continuously at a hydraulic retention time (HRT) of 6 h. The anode effluent was collected in a 100-L rectangular tank placed under the MFC

system and then pumped to the top of the cell array to wet the cathode. When the performance of the MFC system became stable, the HRT was adjusted to 18 h including 12 h for the MFCs and 6 h for the collection tank. For electricity connection, the 12 MFCs in the same row were connected in parallel with an external circuit across a resistor of 2.2 ohm, and then, R1, R3, R5, R7 were connected in serial (R1357) while R2, R4, R6, R8 were connected in serial (R2468), both of which had 15 ohm resistor as external load. The reason why the adjacent rows were not connected in serial was to avoid short circuit connection.

2.2 Electronic connections and energy harvesting device

Four rows of the MFCs (R1, 3, 5, and 7) were used in this study and 4 types of serial connections (S1-4) were examined based on the number of the MFC rows in connection (Fig. S2). S1 had only 1 row as a power source and S4 had all 4 rows connected in serial. S2 (R3 and R7) and S3 (R3, R5, and R7) were the connection with 2 and 3 rows, respectively. To extract electric energy from the MFCs, BQ25504 battery management evaluation module (EVM) board (TI Instruments, TX, USA) was used and modified with a MPPT ratio of 0.5, because the ratio of MPV to OCV is close to a constant (0.5 in most cases) for a functioning MFC system (Fig. 1 and S3). The overvoltage was set at 5 V so that the circuit would stop when the output voltage reached the value [17]. Two serial-connected 5-F ultracapacitors (Maxwell, 2.7V) were used as energy storage media for charging and discharging tests. Fig. S2 shows the schematic of the circuit connection with BQ 25504 EVM and ultracapacitors.

2.3 Measurement and analysis

The voltage and current of the MFC output and the PMS output was recorded every 10 sec by a digital multimeter (2700, Keithley Instruments, Inc., Cleveland, OH, USA). Polarization tests were conducted using a potentiostat (Reference 600, Gamry Instruments, Warminster, PA, USA) at a scan rate of 1 mV s⁻¹. The concentration of chemical oxygen demand (COD) was measured using a colorimeter according to the manufacturer's instructions (Hach Company, Loveland, CO, USA). Total suspended solids (TSS) was measured using standard methods [23]. The power was calculated by eq. (1):

$$P = VI \quad (1)$$

where P is power (W), V is voltage (V), and I is current (A). The conversion efficiency of BQ 25504 was calculated based on eq. (2):

$$\eta = P_{MFC}/P_{BQ} \quad (2)$$

where η is efficiency (%), P_{MFC} and P_{BQ} are power output of MFC and BQ 25504, respectively, based on eq. (1).

3. Results and discussion

3.1 Performance of the MFC system

The performance of the MFC system was briefly summarized in Table 1. The system effectively removed more than 75% organics and 80% solid content. The current generation during regular operation from the S4 connection of the R1357 ranged from 75 to 93 mA with a power output between 84 and 130 mW. Polarization curves with four types of connection are shown in Fig. 1. Among the single row of the MFCs, the R1 produced a maximum power of ~17

mW with a short-circuit current of ~110 mA, lower than that of the R3, R5 and R7 (55, 50, and 65 mW, Fig. S3). When two rows of the MFCs were connected as the S2 (containing R5 and R7), the power output was improved 40% from the S1 (R5 only). When more rows of the MFCs connected to the circuit (S3 and S4), the OCV was increased from 1.6 to 2.4 V but the power was only improved by 10%; the performance of the S3 was even better than the S4. The voltage reversal was not observed as reported from other studies on single MFCs [20, 24, 25]. It seems that the power output of serial connection of multiple MFC rows was affected by the limitation of the weakest current production in each row. In addition, the large difference between the R1 and the other three rows could result in little improvement in the S4 connection.

3.2 Energy extraction and conversion efficiency by using BQ 25504

BQ 25504 was applied to extract energy from the MFC system under four types of connection and to charge the ultracapacitors with charging kinetics shown in Fig. 2. It is obvious that more MFC modules could accelerate the charging process. It took almost 100 min to charge the 5-F ultracapacitors to 5 V with the S1 connection, while the S3 and the S4 connection achieved the same voltage in 8 min. The S3 exhibited better performance than the S4, likely due to the limitation of the R1 on current and voltage (the S3 did not contain the R1). As more MFC modules increased the power output (which was the power input of BQ 25504), the “cold-start” period was significantly shorten from 52 min (S1) to 1 min (S3). The MPPT did not function until the voltage reached ~1.6 V, which was the end point of the warm-up period for self-starting when the input voltage was higher than 300 mV [17]. Therefore, the S1 and the S2 may not have advantage for charging a depleted energy storage element because of a long pre-charging period and a slow charging rate.

170

171 Fig. 3 shows the power output from BQ 25504 and its conversion efficiency applied for
172 different types of serial connection. The S1 (containing only R5) supplied ~30 mW when the
173 MPPT functioned and about 55% power was transferred to charge the ultracapacitors. The S2
174 (R5 and R7) produced 1.6 V OCV and ~100 mW power with much higher efficiency of ~72% in
175 BQ 25504. It was expected that BQ 25504 would be more efficient with a higher input voltage
176 from the S2, not only because of the higher conversion efficiency but also due to the better
177 capability to extract energy from the MFCs with higher power input to BQ 25504. The power
178 production of the S2 was very close to the MPP obtained from the polarization curve, which was
179 ~110 mW and about 9% lower than the total power production of R5 and R7 (Fig. 1C and S3).
180 The S3 (R3, R5, and R7) generated a even higher power input of ~140 mW, which is about 12%
181 lower than the sum of maximum power output from group R3, R5, and R7 (Fig. S3), but 17%
182 higher than that of the S4 (~120 mW). The conversion efficiency with the S3 was over 80%,
183 which is comparable with many other customized converters [10, 26-28]. Higher conversion
184 efficiency of BQ 25504 with the S2 and the S3 indicates that a weak power source (e.g., R1 in
185 this study) could negatively affect the power transfer. In general, BQ 25504 has promoted higher
186 power output at a point close the MPP of the MFCs but could not reduce the negative impact
187 from the weak power source. Therefore, it is critical to cautiously select (grouped) MFCs with
188 similar electrochemical performance as power source when they are connected in serial, and
189 there are many non-global factors causing the variance of power output from the single MFC
190 such as bioactivity, difference in reactor manufacturing, distribution and gradient of substrate
191 concentration, etc.

192

3.3 Charging and discharging

Because the S3 (R357) exhibited the best performance, this connection was examined with the 25 F ultracapacitors for charging/discharging test. The undervoltage and overvoltage for charging was set as 3.5 and 4.5 V, respectively, according to the working voltage of a DC motor (3-5V). As shown in Fig. 4, when the voltage of the ultracapacitors reached 4.5 V, it was discharged by powering the motor and when the voltage was lower than 3.5 V, they were disconnected from the motor and charged by the MFCs until the voltage was 4.5 V. It took ~15 min for the MFC system (S3) to charge the ultracapacitor from 3.5 to 4.5 V during each cycle while the input voltage was maintained at ~1 V, which was close to the half value of OCV as shown in Fig. 1B. BQ 25504 worked well for the MFCs with good conversion efficiency and flexible power management function to charge capacitors. In addition, because the voltage increment by connecting 3 or more MFCs may become less efficient [24], BQ 25504 can be used to stabilize the output voltage level with 3 or less rows of MFCs connected in serial. Although BQ 25504 EVM is designed specifically for DC sources like solar and thermal electric generators and the efficiency can be over 90% as reported by manufacturer, the large variation in current and voltage from the MFCs would result in unsteady MPP that causes the MPPT to function imperfectly with MFCs. It is possible to use this approach to boost output voltage to a higher level like 12 V by a secondary converter system rather than connect 20 or more (grouped) MFCs to minimize the negative effects from weak power source in serial connection.

4. Conclusions

Energy can be effectively extracted from a large-scale MFC system treating municipal wastewater. The power was efficiently converted through BQ 25504 to charge ultracapacitors and run a DC motor. The use of the MPPT promoted energy extraction from the MFCs. The presence of weakly performed MFC modules could negatively impact the performance of the whole MFC system and thus energy extraction/transfer. The successful extraction of the energy from such a large-scale MFC system operated with actual wastewater will encourage further development of this technology for sustainable and energy efficient wastewater treatment. Future investigation will focus on application of the produced energy to offset energy consumption by the MFC system.

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278 **Table 1.** Performance of the MFC system (four groups in serial connection) in contaminants
 279 removal and current production.

Parameters	Influent	Effluent
TCOD (mg L ⁻¹)	156 ± 42	33 ± 15
SCOD (mg L ⁻¹)	67 ± 26	27 ± 8
TSS (mg L ⁻¹)	94 ± 61	14 ± 13
Current production (mA)	75-93	
Power output (mW)	84-130	

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281

282

283 **Figure captions**

284 **Fig. 1.** Polarization curves of the MFCs with four types of serial connection: (A) S4 (R1357), (B)
285 S3 (R 357), (C) S2 (R57), and (D) S1 (R5).

286 **Fig. 2.** Charging profiles of the ultracapacitors by the MFCs with four types of serial connection
287 using BQ 25504.

288 **Fig. 3.** The efficiency of the BQ25504 with different voltage input under four types of
289 connection: (A) S4 (R1357), (B) S3 (R 357), (C) S2 (R57), and (D) S1 (R5).

290 **Fig. 4.** Charging and discharging of the ultracapacitors by the MFC system (S3 connection) and
291 BQ25504.

Figure (1)

Figure (2)

Figure (3)

Figure (4)

Microbial Fuel Cells