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Powering a wireless temperature sensor using sediment microbial fuel cells with vertical arrangement of electrodes

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ABSTRACT

The application of wireless sensors is an important approach for monitoring natural water systems in remote locations; however, limited power sources are a key challenge for successful application of these sensors. Sediment microbial fuel cells (SMFCs) have shown potential as a sustainable power source with low maintenance requirements to power wireless sensors. This study examines electricity generation in lab-scale SMFCs with the sediment from Lake Michigan. Two SMFCs are operated in parallel with a difference in cathode arrangement (floating cathode vs. bottom cathode). The data show that the SMFC with a floating cathode produces more electricity and results in a shorter charging time when an ultracapacitor is connected to the circuit. To control electricity delivery and voltage elevation to a value that can drive a wireless temperature sensor, a power management system (PMS) is developed. With the PMS, both SMFCs can consistently power the wireless temperature sensor for data transmission to a computer, although the number of recorded data within the same period differs. This research provides an effective PMS for power control and valuable experience in SMFC configurations for the next onsite test of the developed SMFCs in Lake Michigan.

1. Introduction

Lake Michigan has a highly important role in the environment and economy of the Great Lakes region of the U.S. [1] and tremendous efforts have been made to study, manage, and protect this vital freshwater resource. To help monitor the environmental and ecological conditions in natural water bodies like Lake Michigan, wireless sensors are frequently used to record the pH, temperature, humidity, aquatic life, and invasive species [2]. Such wireless sensors are powered by either batteries or renewable power sources such as solar panels [3]. Although batteries become more affordable, replacing them in a remote location can be very costly, and solar panel efficiency is challenged by variable weather conditions and the availability of sunlight. Therefore, there is a great need to develop a sustainable power source that can supply power to wireless sensors in remote locations while requiring less maintenance and reducing overall costs. A potential candidate for such a power source is sediment microbial fuel cells (SMFCs), which are simplified microbial fuel cells and can extract bioenergy from sediments through bioelectrochemical reactions [4,5].

SMFCs consist of anode electrodes that are usually embedded in sediment and cathode electrodes installed in water above anode electrodes [6]. Microorganisms living in sediment oxidize organic or inorganic compounds and produce electrons and protons [7,8]. Cathode electrodes, in the location with relatively high dissolved oxygen (DO) concentration, accept electrons and protons for reducing oxygen to water. Unlike conventional MFCs, SMFCs do not contain separators or membranes; instead, DO gradient along the water depth creates different zones (anaerobic/anoxic zone for anode electrodes and aerobic zone for cathode electrodes). SMFCs can be deployed in remote locations and constantly produce electricity [9,10]. Although power production in SMFCs is generally very low, with a proper electric circuit for electricity transfer and storage, SMFCs can power wireless sensors that require electricity at a low frequency [11].

SMFCs have been studied and applied in the field to power wireless sensors; however, studies that focus on the application of an electric circuit to transfer power from SMFCs to drive wireless sensors are still limited. In addition, experiment results highly depend on the locations where SMFCs are installed or on the sediments used in SMFCs [12]. Early efforts include a SMFC installed in a river with a sacrificed anode and biological cathode [13], which powered a temperature sensor through an electric circuit that controlled power charge and boosted voltage to 3.3 V. Tender et al. [14] successfully employed SMFCs to power a meteorological buoy in a marine environment. They investigated two types of SMFCs that could produce a power between 24 and 36 mW, which was sufficient to support the buoy with an average power consumption of 18 mW. Their results provided the first example of using SMFCs to power electronics for a long period of time. Researchers have also

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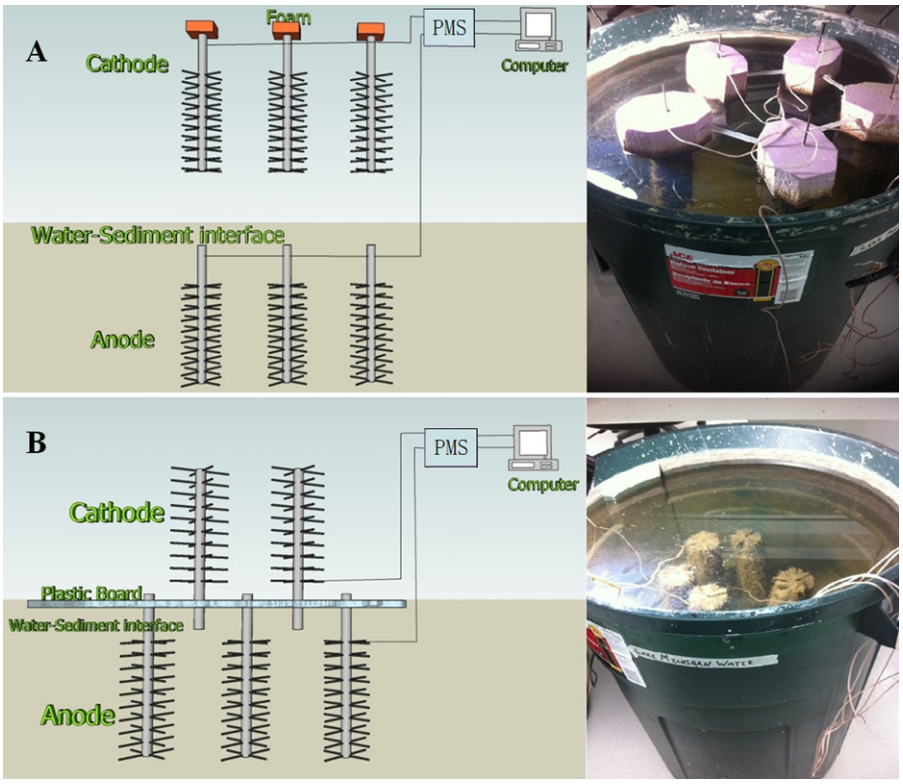

Fig. 1. Schematic and picture of lab-scale sediment MFC: (A) SMFC-1 and (B) SMFC-2.

used deep ocean cold seep to produce electric power in SMFCs [12]. One of the great challenges in SMFC application is power extraction from SMFCs. A recent study developed a power management system that can allow SMFCs to support a 2.5 W sensor [15].

In this study, two lab-scale SMFCs with a difference in cathode arrangement (floating cathode vs. bottom cathode) were operated for more than 5 months. Electricity generation with actual sediment from Lake Michigan was monitored and compared between the two SMFCs. Electrochemical techniques were used to analyze the difference caused by cathode electrodes. A power management system consisting of an ultracapacitor, charge pump, and DC–DC converter was developed and employed to deliver power from the SMFCs to a wireless temperature sensor.

2. Materials and methods

2.1. Sediment MFC setup and operation

Two SMFCs were established in the lab with a notable difference in cathode installation (Fig. 1). Each SMFC was installed in a container that had a total volume of 121 L (height ~70 cm and diameter of the top ~50 cm). Sediments were collected from Lake Michigan and used without any pre-treatment. The sediment layer inside the container was about 25 cm deep and had a volume of ~42 L. The lake water collected from the same location as the sediments was used to fill the container. The water volume was about 68 L.

Carbon brushes (Gordon Brush Mfg. Co., Inc., Commerce, CA, USA) were used as electrode materials for both the anode and the cathode. Each brush (brush part) had a diameter of 5 cm and length of 20 cm. Five carbon brushes were inserted into the sediment as the anode electrode and five brushes were installed in the water above the sediment as the cathode electrode. Before installation, the carbon brushes were pre-treated by immersing in acetone overnight and heating at 450 °C for 30 min to remove the coating layer on carbon fibers and increase their conductivity [16]. No catalysts were applied to any of the electrodes. The cathode electrodes were installed differently between the two SMFCs. In one SMFC (designated as "SMFC-1"), the cathode electrodes hung right below the water surface by connecting each brush to a piece of foam (Fig. 1A). The distance between the anode (top) and the cathode electrodes (bottom) in the SMFC-1 was about 20 cm. In the other SMFC ("SMFC-2") the cathode electrodes were fixed on a plastic board, with the anode electrodes on the opposite side, and installed right above the sediment layer (Fig. 1B). The distance between the anode (top) and the cathode electrodes (bottom) in the SMFC-2 was about 10 cm. The plastic board had multiple holes to allow the exchange of ions or substrates between the sediment and water. Electrodes were connected to an external circuit using copper wires. The portion of the copper wires exposed to water was covered with epoxy to prevent corrosion.

Both SMFCs were operated under a temperature of ~18 °C. Water loss via slow evaporation was compensated with deionized water. No additional carbon source or nutrients were added to the SMFCs. An external resistor of 100 Ω was connected to the electric circuit to start up the SMFC. Once a stable performance was reached, the external resistance was replaced with a power management system that was linked to a wireless temperature sensor (RFTemp101A Data Logger and RFC 101A receiver, MadgeTech, Inc., Contoocook, NH, USA).

2.2. Electrochemical and chemical measurement

The cell voltage was recorded every 5 min by a digital multimeter (2700, Keithley Instruments, Inc., Cleveland, OH, USA). A polarization test was conducted using a potentiostat (Reference 600, Gamry Instruments, Warminster, PA, USA) at a scan rate of 0.2 mV s^{-1}. The pH was measured using a bench-top pH meter (Oakton Instruments, Vernon Hills, IL, USA). The dissolved oxygen was measured using a DO meter (556 MPS, YSI Incorporated, Yellow Springs, OH, USA). A reference electrode (Ag/AgCl) was inserted

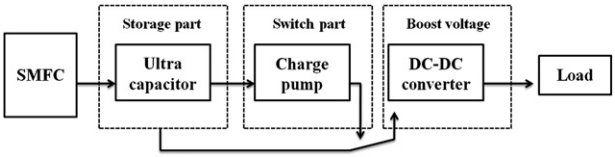

Fig. 2. The developed power management system for storage and transfer of electricity and voltage boost.

in the SMFCs to measure the potential of individual electrode. When an ultracapacitor (Maxwell Technology, Inc., San Diego, CA, USA) was charged from V_d (discharging voltage, close to zero) to V_c (charging voltage), the energy (E_c) stored in the capacitor was calculated as:

$$E_c = 0.5 \times C \times (V_c - V_d)^2 \quad (1)$$

The average energy (E_{avg}) generation in a single charging cycle was calculated by dividing the total energy stored in the capacitor by the charging time, as shown in Eq. (2). The charging time ($t_c - t_d$) was calculated by subtracting the time when the capacitor was discharged (t_d) from the time when the capacitor was charged (t_c)

$$E_{avg} = E_c \times (t_c - t_d)^{-1} = 0.5 \times C \times (V_{c2} - V_{d2})^2 \times (t_c - t_d)^{-1} \quad (2)$$

2.3. Power management system

A power management system (PMS) was designed to store the electric energy, control the power supply, and boost voltage for external application. The PMS, as shown in Fig. 2, consisted of an ultracapacitor (also called super capacitor), a charge pump and a DC–DC converter. The circuit details of the charge pump and DC–DC converter can be found in manufacturers' instruction. The ultracapacitor is an electrochemical capacitor, which has relatively higher energy density than a conventional capacitor, and can be charged in a shorter time compared with rechargeable batteries. The ultracapacitor was used to store the electric energy produced by the SMFCs. The DC–DC converter boosted the low voltage of the SMFCs to a level that could drive the load (e.g., electric fans or wireless sensors). The charge pump acted as a switch to connect or disconnect the ultracapacitor and DC–DC converter.

The DC–DC converter is required for the PMS because the low voltage (<0.9 V) produced by the SMFC is not sufficient to drive a load; however, a direct connection between an SMFC and a DC–DC converter is not practical because a high current is needed to keep the circuit in operation. If an SMFC is directly connected to a DC–DC converter, the output voltage will decrease dramatically and cause the boost circuit to stop working; therefore, an ultracapacitor was placed before the DC–DC converter to store the energy produced by the SMFCs. The DC–DC converter used in this PMS was the TPS61200 from Texas Instruments (Dallas, TX, USA), which can boost the voltage from 0.3 V up to 3.3 V. A voltage of 3.3 V is sufficient to drive many sensors and transmitters.

A practical application requires the PMS to automatically charge and discharge; therefore, a charge pump was connected to the circuit. The charge pump s882z (Seiko Instruments, Inc., Tokyo, Japan) can operate with a voltage as low as 0.3 V with extremely low power consumption. When the charge pump works in a charging mode, it charges a normal capacitor (4700 μF in this circuit) to the discharge-start voltage; during charging mode the output of the charge pump is 0 V. As soon as the voltage of the capacitor reaches the discharge-start voltage, the charge pump turns into the discharging mode, extracting the power stored in the ultracapacitor. When the voltage of the capacitor decreases to discharge-stop voltage, the charge pump stops discharging and turns into the charging mode, completing one cycle. The capacitance of the capacitor is a key factor that affects the period of time of the cycle because it determines the charging mode time. If a charge pump is applied to control the power terminal 'EN' (PIN 6) of the DC–DC converter in the charging mode, the SMFC will disconnect from the load, allowing it to accumulate power to a relatively high level.

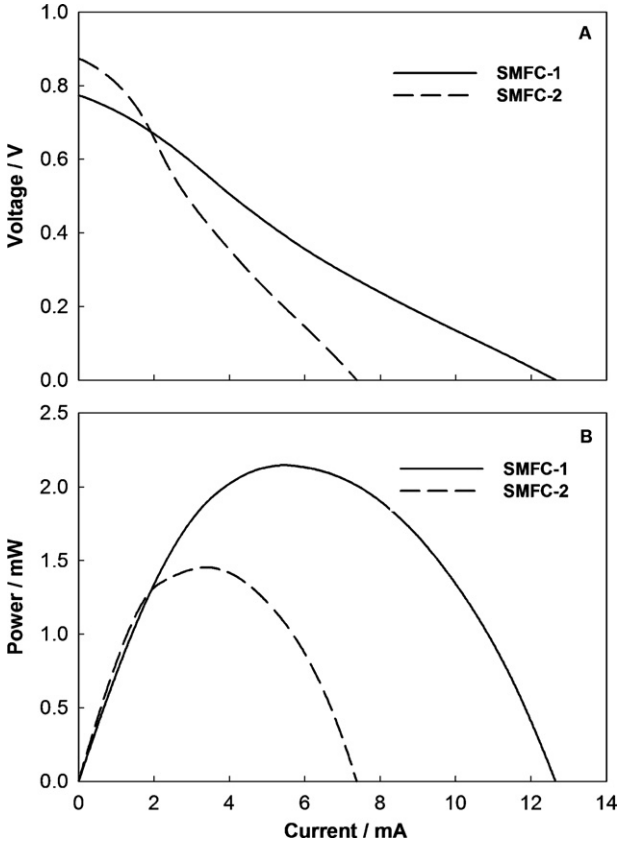

Fig. 3. Polarization results of the SMFCs: (A) voltage curves and (B) power curves.

3. Results and discussion

3.1. Electricity generation from the SMFCs

Both SMFCs operated for more than 5 months in the lab and electricity was continuously produced during the testing period. The open circuit potentials reached 0.77 and 0.87 V in the SMFC-1 and SMFC-2, respectively, comparable to those in other studies [1–3]. Although the SMFC-2 produced a higher open circuit potential, it generally exhibited weaker electricity generation (in terms of power and current) than the SMFC-1 (Fig. 3). The maximum power produced in the SMFC-1 and SMFC-2 were 2.15 and 1.45 mW, respectively. The highest current (short-circuit) was 12.6 mA from the SMFC-1 and 7.4 mA from the SMFC-2.

To understand the difference of electricity generation between two SMFCs, the electric potential of individual electrodes was recorded during the polarization test (Fig. 4). At the zero current, the anode potential of the SMFC-2 was more negative than that of the SMFC-1, resulting in a higher overall open circuit potential; however, it increased much faster over the course of the current increase than the anode potential of the SMFC-1. The cathode potential of the SMFC-1 was more positive at the zero current, and dropped slower after the zero current than that of the SMFC-2.

The profiles of the individual potentials suggest that the cathode is the main limiting factor that resulted in a lower electricity generation in the SMFC-2. This is likely a result of the deeper deployment of the cathode electrode in the SMFC-2, in which the cathode electrodes were installed adjacent to the sediment surface and further

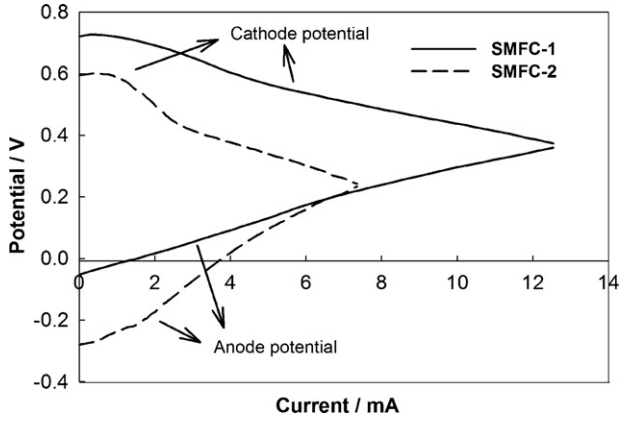

Fig. 4. The potentials of individual electrode (vs. Ag/AgCl) during polarization test.

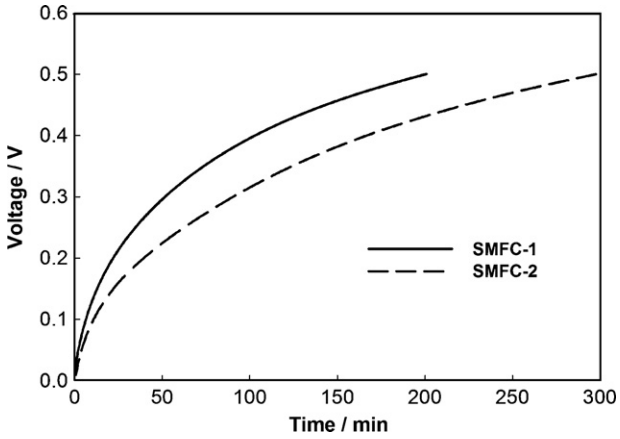

Fig. 5. Charging of a 100-F ultracapacitor by the SMFCs.

from the water surface compared with the cathode of the SMFC-1. Less dissolved oxygen (DO) is present in deeper water. Although the measurement of DO in water showed a very small difference at the same depth between two SMFCs, the DO concentration inside the carbon brush might differ more significantly due to the coverage of the cathode electrodes by biomass (Fig. 1), similar to the DO profile of activated sludge floc [17]. There is possibility that more biomass grows on the cathode electrodes of the SMFC-2 because of its adjacent location to sediment. The DO in water remained relatively high, but the DO inside the carbon brush (close to carbon fibers) could be low due to the microbial metabolism.

The lower anode potential of the SMFC-2 indicated a better anaerobic condition in the SMFC-2, likely due to the use of the plastic board that could prevent oxygen transfer into the sediment; on the other hand, the plastic board might also slow down the transport of cations or anions between the anode and the cathode, which is a key to electricity generation in MFCs. The faster increase of the anode potential in the SMFC-2 could be due to a lower transport of ions, yet further investigation is required. The SMFC-1 seemed to be a more suitable power device than the SMFC-2 because it produced more electricity, but its application in the field faces two major problems. First, such an arrangement of electrodes in deep water will create a large distance between the anode and the cathode, thereby increasing the internal resistance. Second, the floating cathode will be affected by water waves or other activities adjacent to water surface. Nevertheless, the better performance of the SMFC-1 demonstrated the importance of cathode arrangement to electricity generation.

3.2. Ultracapacitor charging

The SMFCs were connected to 100-F ultracapacitors for a direct charging test (without PMS). The highest charging voltage that an ultracapacitor can achieve is determined by the voltage of the SMFCs. In this case, the charging voltage could reach as high as 0.8 V, but it took a substantial amount of time to get 0.8 V. Fig. 5 shows the charging progress to 0.5 V. The difference in electricity generation between the two SMFCs resulted in different charging times. The SMFC-1 needed slightly more than 200 min to charge the 100-F ultracapacitor to 0.5 V, while it took about 300 min for the SMFC-2 to reach the same voltage. A faster charging is more desirable because it can provide more power within the same timeframe, leading to more data recording (Fig. 6).

Charging different ultracapacitors by both SMFCs were also investigated. Clearly, charging smaller ultracapacitors (4.7 and 10 F) took much less time; however, the energy in smaller ultracapacitors (under the same voltage) was much less than in larger ultracapacitors (100 F) (Table 1). We calculated the average energy and the results showed that the 100-F ultracapacitor did not out-compete the 4.7- and 10-F ultracapacitors in energy acquisition per unit time. However, the low capacity of energy storage in smaller ultracapacitors hindered their application when the PMS was incorporated in the electric circuit for wireless sensor powering, which is discussed in the following section.

3.3. Wireless sensor powering

Regardless of the difference in electricity generation and ultracapacitor charging, both SMFCs were able to power wireless temperature sensors and other small electronics such as mini

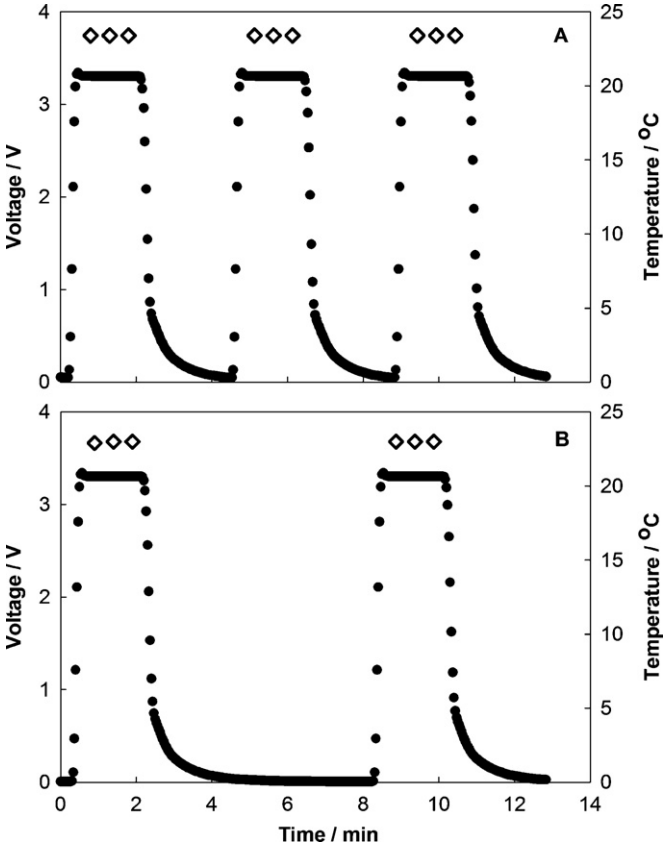

Fig. 6. Voltage variation (●) after DC–DC converter during data recording and temperature data points (◊): (A) SMFC-1 and (B) SMFC-2. A 100-F ultracapacitor was used.

Table 1
Comparison of ultracapacitor charging by the SMFCs.

Ultra-capacitor	Charging time to 0.5 V (min)		Energy at 0.5 V (J)		Average energy at 0.5 V (J min^{-1})	
	SMFC-1	SMFC-2	SMFC-1	SMFC-2	SMFC-1	SMFC-2
4.7 F	8.8 ± 0.9	16.8 ± 0.4	0.59	0.59	0.067	0.035
10 F	22.6 ± 0.7	28.6 ± 2.0	1.25	1.25	0.055	0.044
100 F	210.5 ± 13.7	302.3 ± 5.8	12.5	12.5	0.059	0.041

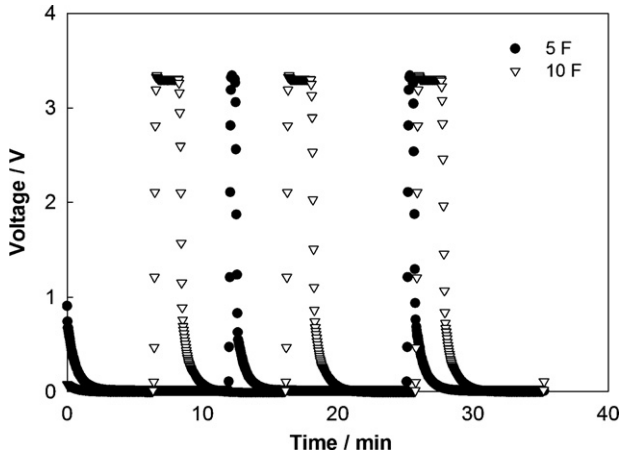

Fig. 7. Voltage variation after DC–DC converter during data recording. It should be noted that although the voltage with 5-F ultracapacitor could be boosted to 3.3 V, it rapidly dropped with connection to the wireless temperature sensor and no data could be recorded due to low energy.

motors and LEDs. Three ultracapacitors (100, 10 and 5 F) were tested for powering a wireless temperature sensor. With the developed PMS, a single charge of a 100-F ultracapacitor could record three readings of the temperature by the wireless sensor (Fig. 6), while the 10-F ultracapacitor could record one reading and the 5-F ultracapacitor did not provide sufficient energy for any readings (Fig. 7). Fig. 8 shows an example of a temperature recording powered by the SMFCs under the control of the PMS (100-F ultracapacitor used). Previously, the SMFC-2 charged an ultracapacitor slower than the SMFC-1 during direct charge (Fig. 5). With the PMS, a similar result was obtained: a single charging of a 100-F ultracapacitor by the SMFC-1 took about 2 min to reach the designed voltage to start the charge pump, while the SMFC-2 required nearly 6 min for the same charging (Fig. 6). This difference may not be critical to applications that do not need highly frequent data recording,

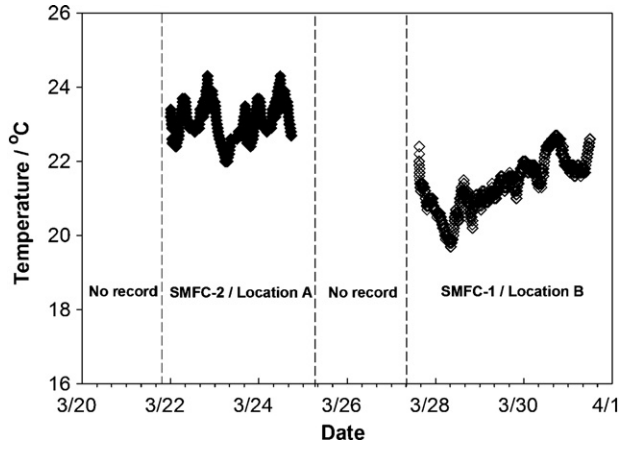

Fig. 8. An example of temperature recording in the wireless sensor powered by the SMFCs under the control of the PMS. A 100-F ultracapacitor was used for energy storage and temperature data were recorded at two different locations.

but it will certainly cause problems when high-energy applications are powered by SMFCs. A faster charging will have more energy accumulation within the time period, which will meet the applications' energy demands.

The ultracapacitors with lower capacitance store less energy than those with higher capacitance at the same voltage. When the voltage of the 10-F or 5-F ultracapacitors reached the specific voltage, it triggered the charge pump and started to transfer energy from the ultracapacitor to the DC–DC converter. Due to the smaller capacity of those ultracapacitors compared with the 100-F ultracapacitor, much less energy is transferred to the DC–DC converter for powering the wireless sensor, thereby supporting fewer records. With the 5-F ultracapacitor, data recording could not be powered at all because of insufficient energy storage in the ultracapacitor when it reached a specific voltage. Increasing the value of the specific voltage of the PMS allows the ultracapacitor to store more energy before triggering the start of charge pump. Different designs of PMS may also work with lower capacitance; for example, Donovan et al. [11] used a 10-F ultracapacitor to power a wireless sensor at the expense of a longer charging time.

The performance of powering wireless sensors by the present SMFCs is comparable to those in other studies. As mentioned above, Donovan et al. [11] employed a SMFC in river to power a wireless temperature sensor similar to the one used in this study. Their SMFC needed more than 100 min to complete one charging for collecting three data points; similar results were reported from another one of their studies [18]. Our SMFCs achieved a much shorter charging time, which we attributed to the larger surface area of the electrodes, a shorter distance between the electrodes, and (possibly) vertical arrangement of the electrode position. Carbon brushes have a higher surface area via their numerous fibers than carbon/graphite plates. This high surface area (of both the anode and the cathode electrodes) provides more reaction sites for redox reactions, thereby increasing electricity production. In addition, the carbon/graphite plates are usually installed horizontally in the sediment, giving them limited access to substrates stored in various depths of the sediment. Our arrangement of electrodes, however, can potentially use substrates at different depths. Furthermore, the extension of the carbon fibers in carbon brushes can further improve the access to substrates. Carbon brushes were used as the anode and the cathode electrodes in the previous SMFC studies, but the anode brushes were either installed above the sediment [12] or in a situation that did not have obvious vertical extension along the depth of sediment [19]. Our study provided possibility of arranging electrodes in a vertical position in sediment for maximizing substrate access.

4. Conclusion

The operation of the SMFCs in the lab has shown a constant production of electricity from Lake Michigan sediment. Comparison of two SMFCs with a difference in cathode installation suggests the floating cathode electrodes led to better performance. Through a power management system, electric energy could be extracted from the SMFC, stored in an ultracapacitor, and used to power a wireless temperature sensor. The study confirmed that a high-capacity ultracapacitor could record more data with the present

PMS, while a low ultracapacitor (5 F) was unable to start the sensor. The results demonstrate the potential of SMFCs as a power supply to wireless sensors and provide valuable experience in SMFC configuration to our next step of installing an SMFC in Lake Michigan for onsite tests.

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References

[1] D. Marcouiller, S. Coggins, System Board of Regents , University of Wisconsin, Madison, WI, 1999.
[2] F. Al-Turjman, M. Ibnkahla, H. Hassanein, WoSPA 2008 – 5th IEEE International Workshop on Signal Processing and its Applications, Sharjah, United Arab Emirates, 2008.
[3] A. Mainwaring, D. Culler, J. Polastre, R. Szewczyk, J. Anderson, WSNA′02 Proceedings of the 1st ACM International Workshop on Wireless Sensor Networks and Applications, ACM, New York, NY, USA, 2002.
[4] C.E. Reimers, L.M. Tender, S. Fertig, W. Wang, Environ. Sci. Technol. 35 (2001) 192–195.
[5] P.R. Girguis, M.E. Nielsen, I. Figueroa, Curr. Opin. Biotechnol. 21 (2010) 252–258.
[6] Z. He, H. Shao, L.T. Angenent, Biosens. Bioelectron. 22 (2007) 3252–3255.
[7] D.R. Bond, D.E. Holmes, L.M. Tender, D.R. Lovley, Science 295 (2002) 483–485.
[8] D.E. Holmes, D.R. Bond, R.A. O'Neill, C.E. Reimers, L.R. Tender, D.R. Lovley, Microb. Ecol. 48 (2004) 178–190.
[9] L.M. Tender, C.E. Reimers, H.A. Stecher III, D.E. Holmes, D.R. Bond, D.A. Lowy, K. Pilobello, S.J. Fertig, D.R. Lovley, Nat. Biotechnol. 20 (2002) 821–825.
[10] J.H. Li, Y.B. Fu, J. Liu, A.L. Li, D.D. Ma, Adv. Mater. Res. 79–82 (2009) 2195–2198.
[11] C. Donovan, A. Dewan, D. Heo, H. Beyenal, Environ. Sci. Technol. 42 (2008) 8591–8596.
[12] M.E. Nielsen, C.E. Reimers, H.K. White, S. Sharma, P.R. Girguis, Energy Environ. Sci. 1 (2008) 584–593.
[13] A. Shantaram, H. Beyenal, R.R.A. Veluchamy, Z. Lewandowski, Environ. Sci. Technol. 39 (2005) 5037–5042.
[14] L.M. Tender, S.A. Gray, E. Groveman, D.A. Lowy, P. Kauffman, J. Melhado, R.C. Tyce, D. Flynn, R. Petrecca, J. Dobarro, J. Power Sources 179 (2008) 571–575.
[15] C. Donovan, A. Dewan, H. Peng, D. Heo, H. Beyenal, J. Power Sources 196 (2011) 1171–1177.
[16] X. Wang, S. Cheng, Y. Feng, M.D. Merrill, T. Saito, B.E. Logan, Environ. Sci. Technol. 43 (2009) 6870–6874.
[17] B. Li, P.L. Bishop, Water Res. 38 (2004) 1248–1258.
[18] A. Dewan, C. Donovan, D. Heo, H. Beyenal, J. Power Sources 195 (2010) 90–96.
[19] M.E. Nielsen, C.E. Reimers, H.A. Stecher, Environ. Sci. Technol. 41 (2007) 7895–7900.