Effect of Growth Solution, Membrane Size and Array Connection on Microbial Fuel Cell Power Supply for Medical Devices

Daniel N. Roxby, *Student Member, IEEE,* Nham Tran, Pak-Lam Yu and Hung T. Nguyen, *Senior Member, IEEE*

***Abstract*— Implanted biomedical devices typically last a number of years before their batteries are depleted and a surgery is required to replace them. A Microbial Fuel Cell (MFC) is a device which by using bacteria, directly breaks down sugars to generate electricity. Conceptually there is potential to continually power implanted medical devices for the lifetime of a patient. To investigate the practical potential of this technology, H-Cell Dual Chamber MFCs were evaluated with two different growth solutions and measurements recorded for maximum power output both of individual MFCs and connected MFCs. Using Luria-Bertani media and connecting MFCs in a hybrid series and parallel arrangement with larger membrane sizes showed the highest power output and the greatest potential for replacing implanted batteries.**

I. Introduction

Microbial Fuel Cell (MFC) technology has captured the fascination of many for their ability to use organic substrates such as sugar to directly generate electricity by means of bacteria. The standard dual chamber MFC (DCMFC) is composed of an anode and cathode chamber separated by a proton exchange membrane (PEM). In the anode chamber are bacteria, an anode electrode, a growth solution and sugar whilst in the cathode chamber is a cathode electrode and a chemical electron acceptor as illustrated in Fig. 1 [1, 2].

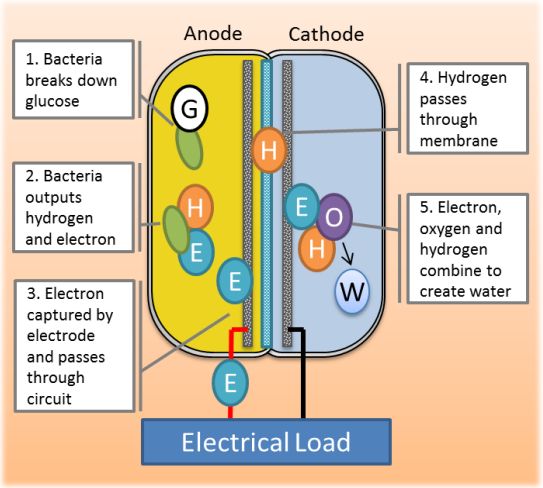

Figure 1. Microbial Fuel Cell Schematic

Daniel N. Roxby, Nham Tran and Hung T. Nguyen are with the Key Centre for Health Technologies, Faculty of Engineering and Information Technology, University of Technology, Sydney, Broadway NSW 2007, Australia. Pak-Lam Yu is from School and Engineering and Advanced Technology, Massey University, Palmerston North 4442 New Zealand.

E-mail contacts: Daniel.Roxby@student.uts.edu.au, Nham.Tran@uts.edu.au, Hung.Nguyen@uts.edu.au, P.Yu@massey.ac.nz

When a microbial population grows, the bacteria will reduce an electron acceptor such as oxygen. The anode electrode is the electron acceptor in a MFC, capturing the electrons, which travel through the electronic circuit and into the cathode chamber via the cathode electrode. The electron is then removed from the electrode by some chemical electron acceptor. In a basic MFC, the bacteria also outputs hydrogen, which travels to the cathode chamber by diffusing through the membrane. Dissolved oxygen in the cathode chamber will link up with the hydrogen and electron to remove the oxygen and create water [1, 2].

Pacemakers and other implanted biomedical devices typically require approximately 30µW of power whilst other devices such as the artificial urinary sphincter are more demanding, requiring 200µW of power [3, 4]. Once all the power is consumed from the battery, surgery is required to replace the power source. Surgery is not the preferred option as there is an inherent risk to patients who are already in poor health. Radio Frequency charging through the skin has undergone several developments, but heating of the skin is still a major issue coupled with prolong periods of charging [3]. Movement is usually required of the user for kinetic energy harvesting systems, solar cells cannot be implanted and maintaining temperature gradients for thermal energy harvesting is difficult. Parts of the body have well regulated levels of glucose and oxygen which could replenish a MFC. This source of energy could potentially drive a MFC far beyond a normal battery.

Many MFC studies have focused on their use in biomedical applications; however more research is required to fully realized this potential [5-8]. In these studies, bodily fluids are often used within the MFC; however this is most likely to cause disruption, possible infection and rejection of the implant within the patient. Previous work by Roxby et al has also shown that a single MFC cannot provide sufficient voltage to operate a biomedical device [9, 10]. In this study, we focused on Luria-Bertani (LB) broth and Tryptic Soy Broth (TSB) to optimize power output in single self-contained MFC or multiple arranged MFCs. Additionally we also investigated the effect of two different membrane sizes (25 mm and 40 mm) on the MFC output [11].

II. Experimental Method

A. Microbe and Growth Conditions

Laboratory stocks of *Shewanella oneidensis MR-1* were chosen as the inoculate for our experiments for its exoelectrogenic capabilities and was originally purchased from the American Type Culture Collection (ATCC 700500) [12]. A Tryptic Soy Agar plate was streaked from laboratory stocks and grown for the standard overnight period (16 to 18

hours) in a 30°C incubator. From this, a single colony was picked and placed in to 50mL of Tryptic Soy Broth (TSB) in a 200mL Erlenmeyer flask and shaking incubated for the overnight period at 30°C and 200 R.P.M. Each DCMFC was inoculated with 100µL of cells into the DCMFC anode. CFU counts were tested to be within 1 to 10 x 10^8 CFU/mL with the drop plating method.

B. MFC Materials

Autoclaved (121°C, 20 minutes) H-Cell MFCs purchased from Adam's Chittenden Scientific glassware contained 100 mL of either TSB or LB broth as the anolyte and 100 mL of Phosphate Buffer Solution (PBS) at pH 7.0 as the catholyte. Nafion-117 with diameters of 25 mm and 40 mm were used as the separating membrane. The electrodes were Reticulated Vitreous Carbon (RVC) of 30 mm x 30 mm x 0.5 mm size, having an approximate surface area of 0.02775 m^2 (Goodfellow Corp.). Titanium wire of diameter 0.5 mm insulated with heat shrink tubing was used in twisted pair along with conductive silver epoxy to connect the wire to the electrodes (CircuitWorks CW2400). The assembled wire with electrodes and membrane were exposed to UV for 10 minutes on each side for sterilization purposes.

C. Measurement Setup

During the first 6 to 7 days of MFC operation, the open circuit voltage of the MFCs were logged every 10 seconds, and then polarization curves were taken with resistors connected at 3.9MΩ followed by a stepping down in resistance until the voltage equaled zero. With each change, the voltage was left to stabilize for at least 10 minutes and then the voltage measured. Measurements were taken with a National Instruments USB-6009 connected to a Windows PC with a custom LabView program in differential measurement mode. Output current was calculated by Ohm's law (V = IR). Area and volumetric maximum current and power output are referred to the electrode surface area and total combined chamber volume respectively. For each LB and TSB experiment, MFCs were run in triplicate in the same environment at room temperature and each set of MFCs were inoculated from the same overnight culture.

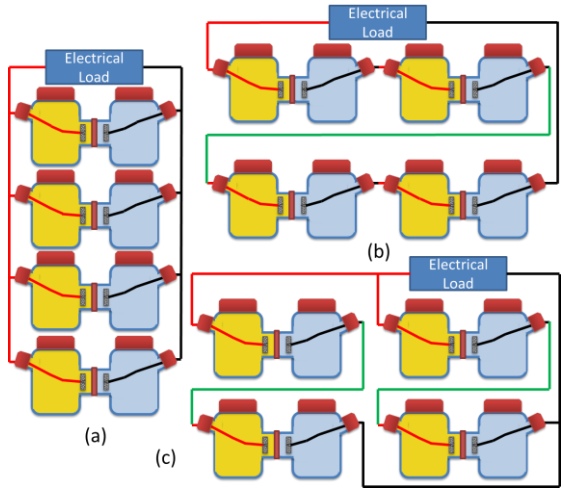

Figure 2. MFC Array connections. (a) Parallel, (b) Series (c) Hybrid Parallel-Series

C. Arrays of DCMFCs

After running four LB DCMFCs for the 6 to 7 day period, then conducting the individual polarization and power curves with them, the DCMFCs were connected in the arrays shown in Fig. 2 where further polarization and power curves data were taken by the method described in the previous section. The MFCs were left in open circuit for 24 hours between array experiments to permit voltage recovery.

III. Results and Discussion

To test self-contained MFCs that would not rely on the human body and were separate from it, TSB and LB DCMFCs were tested. During these tests, the MFCs were left firstly in open circuit for approximately 6 to 7 days which allowed a microbial population and voltage to develop. To test their ability to deal with an electrical load, various resistances were connected and the power calculated. Following this, to further test the potential to turn on a device, arrays of DCMFCs were setup and their voltage monitored after various resistances were connected.

The voltages developed in open circuit mode for both the LB and TSB DCMFCs over a 6 to 7 day period are shown in Fig. 3. During the running of the LB MFC, the peak voltage reached was 464.557 mV and occurred on the sixth day of the running of the MFC. This is compared to a peak voltage of 332.86 mV occurring again on the sixth day for the TSB MFC.

In the first two days of the running of the MFC experiments, the TSB voltage increased by approximately 200 mV in the first day, whilst the LB MFC's voltage increased from the second day by approximately the same amount. The TSB voltage was mostly stable by the second day onwards, whilst the LB voltage seemed to continue to increase until it leveled off in the final day.

B. TSB and LB Polarization and Power Curves

The polarization curves for the TSB and LB MFCs are shown in Fig. 4. For the TSB MFC, the values ranged from 451.02 mV at 0.115 µA to 70.8 mV at 70.8µA. This is in comparison to 328.82 mV at 0.084 µA to 13.42 mV at 16.37 µA. The *S. oneidensis MR-1* population grown from LB is clearly better able to support a higher voltage and current than that grown by the TSB.

Fig. 5. shows the power curves for the LB and TSB MFCs taken after the 6 to 7 day open circuit growth period. The peak power for the TSB DCMFC was found to

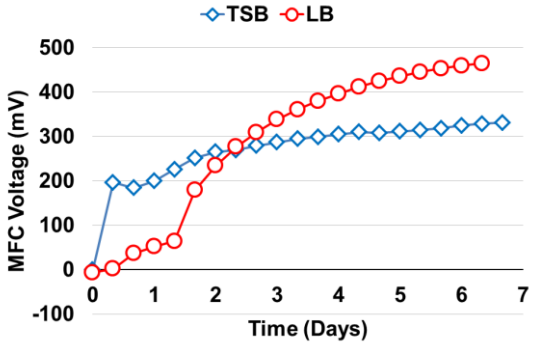

Figure 3. LB and TSB Voltages for open circuit DCMFCs over 6 to 7 days

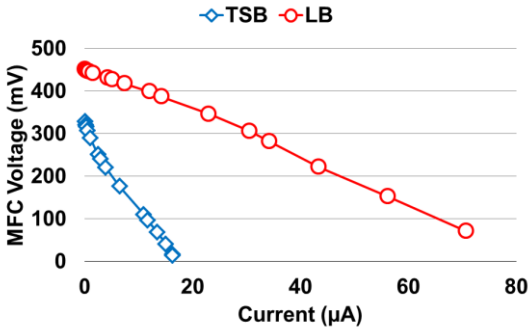

Figure 4. Polarization Curves for LB and TSB DCMFCs after various resistances were connected

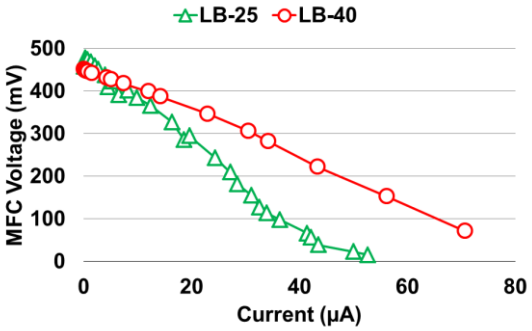

Figure 6. Polarization Curve for LB DCMFCs with 25 mm and 40 mm membrane sizes

be 1.23 mW at 11 µA which was almost 8 times lower than the LB MFC peak power of 9.68 mW at 34.31 µA. Since the peak power occurs when the internal and external resistance are matched, the internal resistance for the TSB MFC is 10000 Ω and for the LB DCMFC is 8200 Ω. Since there is minimal difference between the resistances, the difference in MFC output may be coming purely from the bacteria and the growth media, since all other components of the system remain the same.

This is a good result in terms of potential for MFC technology to power implanted biomedical devices since pacemakers can operate off approximately 30 µW. At this stage though, from individual DCMFCs, it is not possible since the voltage is too low to be able to turn on a device. One possibility to accommodate this lies in the use of a DC-DC converter. A LTC3109 Evaluation Board was connected to the LB DCMFCs and the voltage collapsed. 5V was measured at the output of the Evaluation Board, however when a LED was connected, no light could be seen, possibly due to the need for a higher current.

C. Comparison of Different Membrane Sizes in DCMFCs

One of the many aspects of a MFC is its structural design, which would impact on the chemical dynamics within the reactor. To further understand the impact that the membrane size structural design of DCMFCs has on the MFC output, two different membrane sizes were used in the LB MFCs. LB was chosen as the media here since it was the better performing of the growth media.

Fig. 7 shows the polarization curves for the 25 mm and 40 mm. The voltage is overall higher for the larger membrane, giving an average of 304.28 mV, whilst for the small membrane the average voltage was 286.73 mV. The results for the power curve follow this trend, showing that the peak power from the 40 mm membrane MFC is 9.68 mW whilst for the 25 mm membrane MFC is was 5.94 mW. This represents 1.6 fold increase in power by simply designing for a larger membrane size and is perhaps due to a greater area for the hydrogen to flow through the membrane to complete the reaction in the cathode chamber.

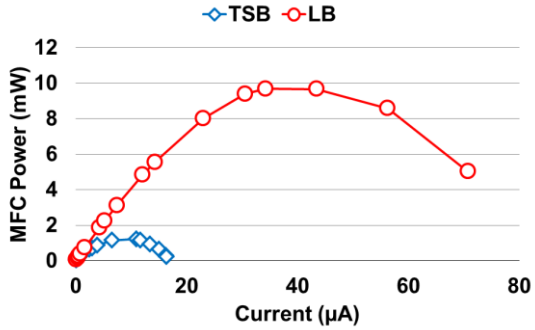

Figure 5. Power Curves for LB and TSB DCMFCs after various resistances were connected

D. Polarization and Voltage Curves of Arrays of MFCs

To test what the effect of connecting several MFCs together in different configurations may have on the voltage and current output, 4 LB MFCs were connected together and polarization and power curves were taken and shown in Fig. 8 and Fig. 9 respectively. In the two curves, the results are what are expected when connecting several power sources together.

For the series connected array, the voltage is higher, starting at approximately 4 times the individual MFC at 1619.38 mV at 0.45 µA and ranged down to 33.92 mV at 66.51 µA. In the parallel connected array, the voltage began at 490.56 mV at 0.257 µA and ranged down to 102.105 mV at 378.17 µA which is approximately 4 times the current output of an individual DCMFC. Lastly, in the Parallel-Series connected setup designated by 'PS', the maximum and minimum voltage and current are approximately midway between the series and parallel setups ranging from 913 mV at 0.23 µA to 70.71 mV at 261.89 µA.

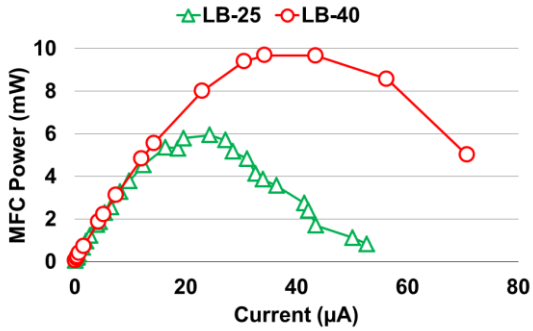

Figure 7. Power Curve for LB DCMFCs with 40 mm and 25 mm membrane sizes

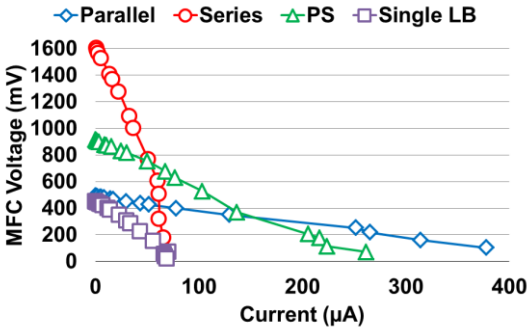

Figure 8. Polarization Curve for MFC Arrays

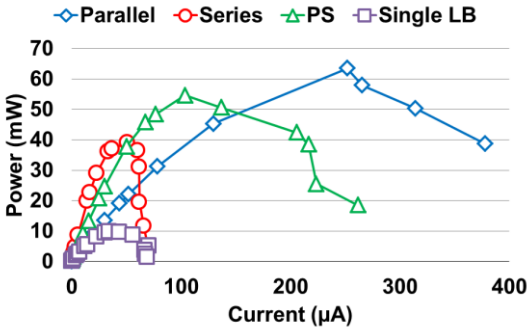

Figure 9. Power Curve for MFC Arrays

The series array in the power curve seemed to provide the least power, giving a peak of 39.07 mW at 51.04 µA, the parallel array gave a peak of 63.47 mW at 251.94 µA and again the PS setup gave a midway between the series and parallel setups at 54.64 mW at 103.51 µA. The respective internal resistances were 15000 Ω, 1000 Ω and 5100 Ω for the various connected arrays and are expected when connecting resistances in this way, except in the case of the series connection where it appears lower.

Our results further indicate the potential to power implanted biomedical devices using bacteria. In each of the connections, the power is sufficient to operate electrical devices. The parallel result demonstrates that adding DCMFCs together can increase the current over a single DCMFC, whilst the series connection shows that by adding DCMFCs provides greater voltage. The hybrid series-parallel connection allows for increases in both. Further work could investigate these setups in longer term experiments.

IV. Conclusion

If MFCs are to be implantable, to avoid infection of the patient, they will need to be able to contain the bacteria from the body. A self-contained MFC then is required and in this study, we show that a LB MFC has the potential to fulfill these criteria. LB also showed a 7.9 fold increase in power over a TSB MFC.

Despite the increases in power between the two growth media, one MFC is not enough to turn on electronic devices due to the low current and voltage. Interestingly by increasing the size of the membrane from 25 mm to 40 mm, a current increase of 1.6 fold was observed. To increase the voltage, several MFCs were connected in different arrays. The series connected array increased the voltage, but could not achieve a high power. The parallel connection gave high current output but a low voltage. In contrast, the hybrid series-parallel connection had increases in both the voltage and current.

Whilst there is much potential for MFCs to power implanted biomedical devices, there are many challenges ahead. The laboratory based MFCs, despite using a self-contained approach, would still need significant work to be safe to be implanted inside the human body. Further work could address the longevity and stability of these MFCs. Additionally, if MFCs are connected in an array long term, the electrochemical environment may not suit the bacteria.

Acknowledgment

Many thanks go to the Centre for Health Technologies, for the funding and assistance through this project. Much support was also given by the Level 7 PC2 Microbiology Laboratory of the University of Technology, Sydney.

References

[1] K. Rabaey and W. Verstraete, "Microbial fuel cells: novel biotechnology for energy generation," *Trends Biotechnol,* vol. 23, pp. 291-8, Jun 2005.

[2] B. E. Logan, B. Hamelers, R. Rozendal, U. Schröder, J. Keller, S. Freguia*, et al.*, "Microbial Fuel Cells: Methodology and Technology†," *Environmental Science & Technology,* vol. 40, pp. 5181-5192, 2006/09/01 2006.

[3] X. Wei and J. Liu, "Power sources and electrical recharging strategies for implantable medical devices," *Frontiers of Energy and Power Engineering in China,* vol. 2, pp. 1-13, 2008/03/01 2008.

[4] H. Lamraoui, P. Mozer, G. Robain, A. Bonvilain, S. Basrour, P. Gumery*, et al.*, "Design and implementation of an automated artificial urinary sphincter," in *International Workshop on Wearable Micro and Nanosystems for Personalised Health (Phealth'08)*, 2008.

[5] Y. Han, C. Yu, and H. Liu, "A microbial fuel cell as power supply for implantable medical devices," *Biosensors and Bioelectronics,* vol. 25, pp. 2156-2160, 2010.

[6] K. Dong, B. Jia, C. Yu, W. Dong, F. Du, and H. Liu, "Microbial fuel cell as power supply for implantable medical devices: A novel configuration design for simulating colonic environment," *Biosensors and Bioelectronics,* vol. 41, pp. 916-919, 2013.

[7] C. P. B. Siu and C. Mu, "A Microfabricated PDMS Microbial Fuel Cell," *Microelectromechanical Systems, Journal of,* vol. 17, pp. 1329-1341, 2008.

[8] F. Qian, M. Baum, Q. Gu, and D. E. Morse, "A 1.5 µL microbial fuel cell for on-chip bioelectricity generation," *Lab on a Chip,* vol. 9, pp. 3076-3081, 2009.

[9] D. N. Roxby, N. Tran, and H. T. Nguyen, "A simple microbial fuel cell model for improvement of biomedical device powering times," in *Engineering in Medicine and Biology Society (EMBC), 2014 36th Annual International Conference of the IEEE*, 2014, pp. 634-637.

[10] D. Roxby, N. Tran, P. Yu, and H. Nguyen, "PERPETUALLY POWERING BIOMEDICAL DEVICES WITH MICROBIAL FUEL CELLS," *Presented at the Australian Biomedical Engineering Conference (ABEC), Melbourne, Australia. Retrieved from, http://www.abec.org.au/wp-content/uploads/2015/10/10.30-Roxby-abstract.pdf*

[11] D. N. Roxby, N. Tran, P.-L. Yu, and H. T. Nguyen, "Experimenting with microbial fuel cells for powering implanted biomedical devices," in *Engineering in Medicine and Biology Society (EMBC), 2015 37th Annual International Conference of the IEEE*, 2015, pp. 2685-2688.

[12] Y. A. Gorby, S. Yanina, J. S. McLean, K. M. Rosso, D. Moyles, A. Dohnalkova*, et al.*, "Electrically conductive bacterial nanowires produced by Shewanella oneidensis strain MR-1 and other microorganisms," *Proceedings of the National Academy of Sciences,* vol. 103, pp. 11358-11363, 2006.