

Development of a Nitrifying Microbial Fuel Cell for Sustainable Wastewater Treatment

Jeremy S. Guest¹, Sayangdev Naha², Ross Frey², Josh Sole³, Nancy G. Love^{1,4}, Ishwar K. Puri², and Michael W. Ellis³

¹Dept. of Civil and Environmental Engineering, ²Dept. of Engineering Science and Mechanics, ³Dept. of Mechanical Engineering, and ⁴Dept. of Biological Sciences, Virginia Tech

ABSTRACT

Wastewater treatment is an energy intensive process that removes contaminants and protects the environment. While some wastewater treatment plants (WWTPs) recover a small portion of their energy demand through sludge handling processes, most of the useful energy available from wastewater remains unrecovered. Efforts are underway to harness energy from wastewater by developing microbial fuel cells (MiFCs) that generate electricity. To date, MiFC technology based on wastewater treatment has focused on utilizing energy from carbon metabolism; despite its potential benefits, this approach has been plagued with inefficiencies. We propose to overcome these problems using nanoparticle-enhanced anode designs that can improve the transfer of electrons from cells to the anode. Furthermore, we propose to expand the matrix of bacterial metabolisms that can be used with MiFCs to include microaerobic nitrification. Nitrifying MiFCs can help treatment plants meet reduced nitrogen discharge goals and provide a revenue stream that offsets the large cost of achieving reduced nitrogen loading. As the wastewater industry enters the nutrient trading era, having alternative, revenue-generating nitrogen removal technologies could provide a substantive incentive for sustainable wastewater management.

We have developed a novel nitrifying MiFC that contains a nanostructure-enhanced anode, which has successfully achieved power generation of 43 mW/m² over 9 hours (comparable to early achievements by carbon MiFCs). Overall, this technology has the potential to significantly reduce wastewater treatment plant operating costs and make the larger-scale implementation of MiFC technology far more feasible. The outcome would be a technology that could produce at least 1.4 GW-hours/day (30% efficiency assumed) of the ammonia in domestic sewage at treatment facilities across the United States (worth approximately \$54 million/yr in energy costs, assuming \$0.10/kW-hr). The impact is far greater if industrial wastewaters are considered.

BACKGROUND

MiFCs – Microbial fuel cells are comprised of an anode and a cathode, often separated by a proton exchange membrane (PEM). Within the anode compartment, electron donors are oxidized by bacteria, resulting in free electrons and protons. The bacteria then transfer the electrons to the anode, an insoluble electron acceptor. Once the electrons are deposited on the anode, they travel through an external circuit (generating electricity) as the protons travel through the wastewater and PEM. Finally, the electrons and protons travel to the cathode where oxygen is reduced to form water.

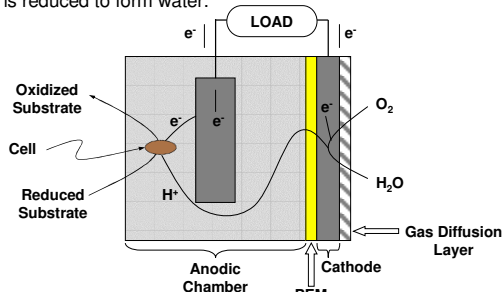
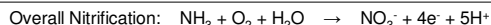


FIGURE 1 – A single chamber microbial fuel cell.

BACKGROUND (cont.)

Nitrification – Aerobic ammonia oxidation is a two-step process that converts NH₃ to NO₂⁻ via enzymes ammonia monooxygenase (AMO) and hydroxylamine oxidoreductase (HAO). This process, coupled with NO₂⁻ oxidation to NO₃⁻ by nitrite oxidizing bacteria (NOBs), generates 4 electrons:



Carbon Nanostructures – Carbon nanotubes/nanofibers (CNTs/CNFs) can be produced via combustion synthesis on various substrates. Anodic substrates are typically conducting materials that are templated with catalytic nanoparticles, e.g., iron and cobalt, that allow for carbon nanostructure growth.

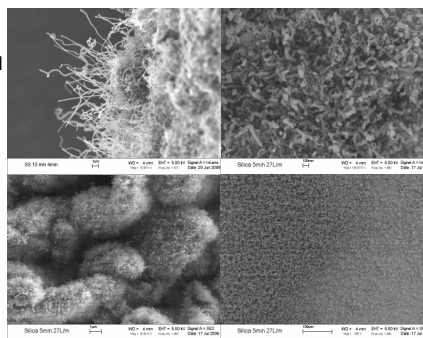


FIGURE 2 – Scanning electron microscopy (SEM) images of flame synthesized CNTs/CNFs produced for MiFC anodes.

EXPERIMENTAL APPROACH

A prototype, single chamber MiFC was constructed and operated using the following materials:

Anode – Stainless steel mesh with flame synthesized CNTs/CNFs

Cathode – Platinum catalyst painted on PEM surface

PEM – Nafion 117 proton exchange membrane

Gas Diffusion Layer – Porous carbon paper

Chamber – Plexiglas® cylinder with polycarbonate end plates (volume of ~ 100 mL)

Inocula – *Nitrosomonas europaea*

Substrate – Ammonia (NH₃)

Immediately preceding each batch experiment, the prototype MiFC was inoculated and ammonia was added. The MiFC was then connected to a potentiostat and a polarization curve was generated. The power curve was then plotted and the optimum voltage for a given run was determined (designed to achieve maximum power production). Finally, the potentiostat was used to maintain the optimum voltage and each batch experiment was run until current production was less than 5 μA.

MiFC Batch Experiments

Abiotic Control – Sterile media with a stainless steel anode with carbon nanostructures.

Biotic Control – Inoculated media with a stainless steel anode without carbon nanostructures.

MiFC Run – Inoculated media with a stainless steel anode with carbon nanostructures.

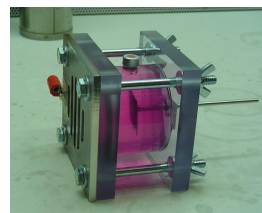


FIGURE 3 – A single chamber MiFC was constructed and multiple batch studies were performed.

RESULTS

FIGURE 4 – Power curve for prototype MiFC run using *Nitrosomonas europaea*-enriched nitrifying culture with cells plus nanotubes (Experimental), a nanotube anode without cells (Abiotic Control), and a regular anode with cells but no nanotubes (Biotic Control).

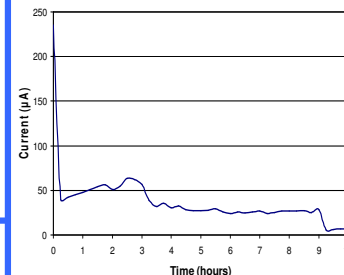
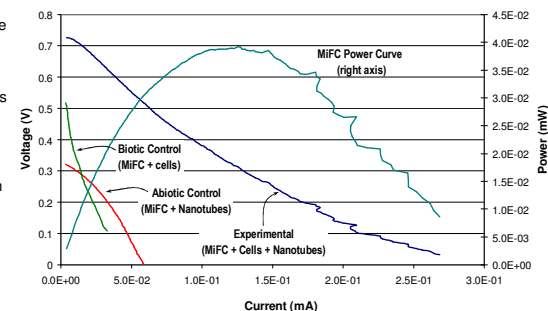


FIGURE 5 – Graph of current generation by prototype MiFC during experimental batch run. Voltage was held constant at 0.5 V. No appreciable current (> 5 μA) was produced by the biotic or abiotic controls (data not shown).

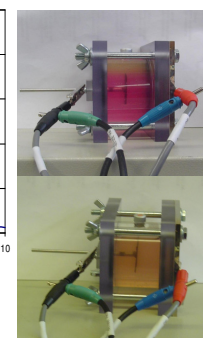


FIGURE 6 – Prototype MiFC containing an enriched nitrifying culture and ammonia growth media. The anode chamber contained media indicator that changes to yellow once acid is formed by the nitrification reaction. **Top:** MiFC shortly after starting batch test. **Bottom:** MiFC two days later. The yellow color corresponded to 25 mg/L nitrate production (as N). There was no increase in NO₃⁻ or NO₂⁻, nor change in pH in abiotic control (data not shown).

CONCLUSIONS

- We confirmed the generation of oxidized nitrogen species during two days of batch operation, and obtained 43 mW/m² of power over the first 9 hours.
- We generated enough electricity during the batch experiment to operate a modern pacemaker for 31 hours or a hearing aid for 18 minutes.
- **Our preliminary results clearly show the benefit of coupling the nanostructure-enhanced anode with nitrifying bacteria.**
- This development could also benefit organic carbon oxidizing MiFCs.

FUTURE WORK

- Develop various nanostructure-enhanced anode designs and evaluate nitrifying biofilm formation on each.
- Optimize O₂ flow in the anodic chamber to maximize system efficiency.
- Develop a flow through nitrifying MiFC that is maintained under optimal conditions.
- Screen various growth conditions to identify those that enhance pili formation in *Nitrosomonas europaea* for enhancement of electron transfer via microbial nanowires.

ACKNOWLEDGMENTS

NSF Materials and Processes for Proton Exchange Membrane Fuel Cells Program