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The Effect of Anode Surface Area on the Power Generation of a Pond Sludge Microbial Fuel Cell

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Abstract

In this paper, a new anode design for microbial fuel cells (MFCs) is proposed. It is hypothesized that a curved anode design will change the power output of a pond sludge glucose powered MFC. Two MFCs were constructed using 3D printed parts, gaskets, and threaded rods. These MFCs were filled with pond sludge and an inoculum containing fuel and buffer nutrients. The two cells were run for 24 hours hooked up to an Arduino power measuring circuit. After data collection, a significant difference was seen in the power output of both cells. The curved anode MFC had a lower power output when compared to the flat anode MFC.

Introduction

Microbial fuel cells (MFCs) are an exciting new power generation technology. Microbial fuel cells use the oxidative process of cellular respiration in bacteria to generate electrons. The bacteria can use a fuel solution for cellular respiration. Microbial fuel cells use specialized bacteria which use cytochromes or nanowires on their bodies to conduct the electrons produced in anaerobic cellular respiration out of the bacteria to an electrode (Sure). These bacteria use metals or other elements as their final electron acceptors, as opposed to oxygen. Certain anaerobic bacteria, called exoelectrogenic bacteria, possess the ability to do this. These species of bacteria can be found in pond sludge or wastewater. Microbial fuel cells are appealing because they can allow for eco-friendly power generation through ubiquitous fuels such as glucose.

Despite their promising nature, MFCs have many shortcomings. They have low voltage and current outputs, and current MFC designs have not been able to increase either of those quantities to a point where they can be used in commercial applications. However, there is one factor that has not been considered in these designs: electrode surface area. Increasing electrode surface area can increase voltage, decrease resistance, and increase current in normal cells (Das). This can be done without increasing the size of the fuel cell by making the anode shape curved, as seen in the cristae of mitochondria. A microbial fuel cell with a high surface area anode could theoretically improve power output for a cell, making it more appealing for practical purposes.

This study looked at the effects of anode surface area on MFC power production. Two single chambered MFCs were constructed, one with a flat anode and one with a curved anode. The anodes were made out of carbon cloth (Zielke). These carbon cloths served as the final electron acceptors for the bacteria. Both MFCs lacked proton exchange membranes (PEMs) as they were unnecessary for ion transfer across the cell (Liu). A platinum air cathode with a silicone gas diffusion layer was used (Kim). The cells were constructed using 3D printed parts and held together using threaded rods and rubber gaskets. Power was measured using an Arduino and two INA219 current and voltage sensors (Ada).

Objective: The objective of this study was to ascertain whether a pond sludge, glucose metabolizing single chambered MFC with a high surface area anode will have a significantly different power output from a flat anode MFC.

Assumptions: The researcher assumed that the bacteria will respire at a constant rate and operating conditions for both fuel cells will remain similar.

Expectations: The expectation for this study was to see a positive difference between the curved anode MFC power output and the flat anode MFC power output. However, the hypothesis and statistics tested for either a positive or a negative difference, to account for the fact that a negative difference could potentially be observed.

Hypothesis

Alternate: *There will be a significant difference in the power output of a single chambered MFC with a curved anode and an MFC with a flat anode.*

Null: There will be no difference in the power output of a single chambered MFC with a curved anode and an MFC with a flat anode.

Methodology

Materials

Material	Supplier	Quantity
Rubber gasket	Amazon	3 sheets (20 cm*20 cm)
Carbon paper	Fuel Cell Store	1 sheet (20 cm*20 cm)
Titanium wire (0.5 mm)	Amazon	1 spool
0.5 mg/cm^2 40% Pt on Carbon Paper	Fuel Cell Earth	2 sheets
Crocodile clip wires	Researcher	4
Jumper wires	Researcher	16
Wing nuts 10-32	Grainger	12
Pond Sludge	Brookdale Community College Pond	110 ml
Glucose powder	Patel Brothers (Store)	0.4 g
Threaded rods 10-32 3 ft	Grainger	3
PLA Fiber	Amazon	2 spools
Silicone Spray	Amazon	1 can
Biological Oxygen Demand (BOD) pillows	Hach	3 pillows
Sodium phosphate monobasic	HTHS	1.4 g
Sodium phosphate dibasic	HTHS	1.4 g
Rubber stoppers size #00	Amazon	4
Dechlorinated water	HTHS	1 L
Breadboard	Researcher	1
1 L beaker	HTHS	3
SD card	Researcher	1

Equipment

Equipment	Supplier	Quantity
3D Printer	Rohit Chaudhri	1
Dremel Multi-tool	Researcher	1
Autodesk Inventor	Researcher	1
Arduino	Researcher	1
INA219 Current and Voltage sensor	Adafruit	2
MicroSD card reader	Adafruit	1
Macbook Air with Arduino IDE	Researcher	1
Shovel	HTHS	1

Area

Area	Supplier	Quantity
Home with Work Bench	Researcher	1
3D printing area	Rohit Chaudhri	1
Research Lab	HTHS	1
Pond	BCC	1

EDD

Title:	The Effect of Anode Surface Area on the Power Generation of a Pond Sludge Microbial Fuel Cell
Hypotheses:	Alternate *There will be a significant difference in the power output of a single chambered MFC with a curved anode and an MFC with a flat anode.* Null There will be no difference in the power output of a single chambered MFC with a curved anode and an MFC with a flat anode.
Independent Variable	Anode structure (Curved or Flat)

Levels:	Curved Anode	Flat Anode
Number of Trials:	24	24
Control?		Yes

Dependent Variable	Power
Operational Dependent Variable	Power (Current*Voltage)
Constants	Cathode material (Pt Carbon Paper) Operational conditions (time, temp, etc.) Measuring tools (INA219) Anode material (Carbon paper) Fuel cell design (one chambered) Microbes (Pond sludge) Fuel (Glucose) Fuel cell run time (24 hours)

Experimental Setup/Diagrams

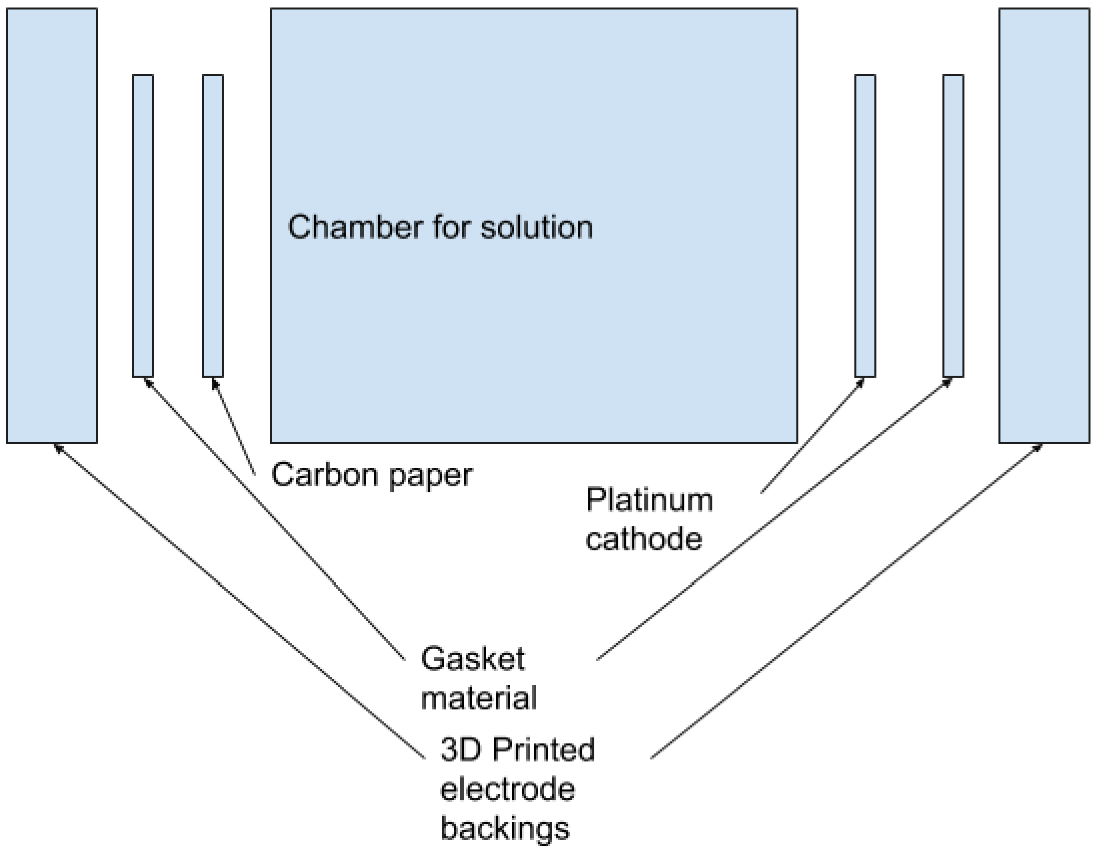

Fig 1. Assembly of MFC

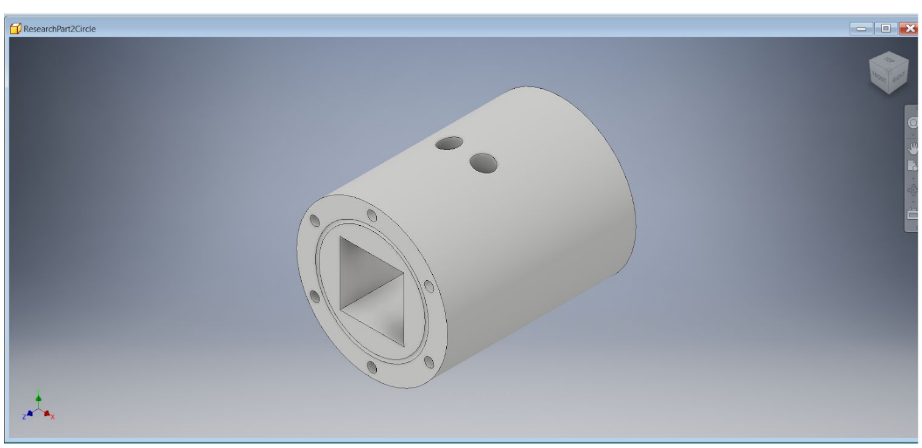

Fig 2. Model of MFC Chamber

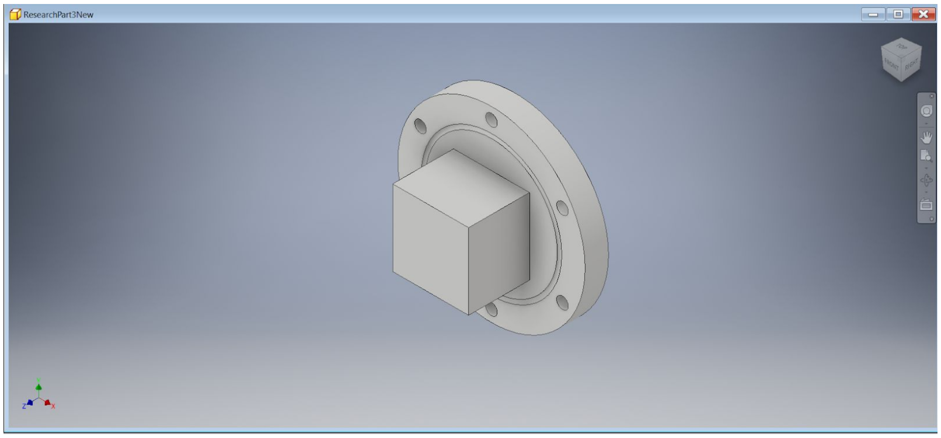

Fig 3. Model of Flat Anode Backing

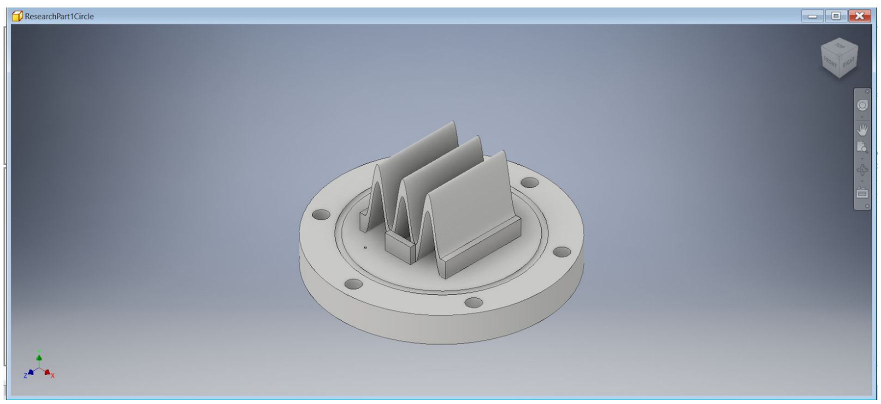

Fig 4. Model of Curved Anode Backing

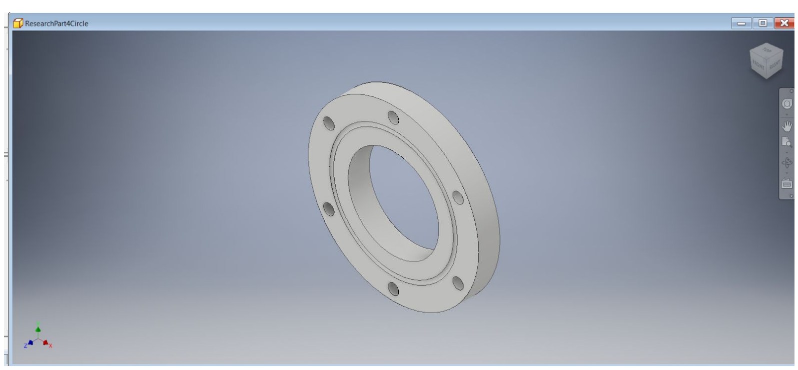

Fig 5. Model of Cathode Backing

Fig 6. Flat Anode MFC Assembled

Fig 7. Curved Anode MFC Assembled

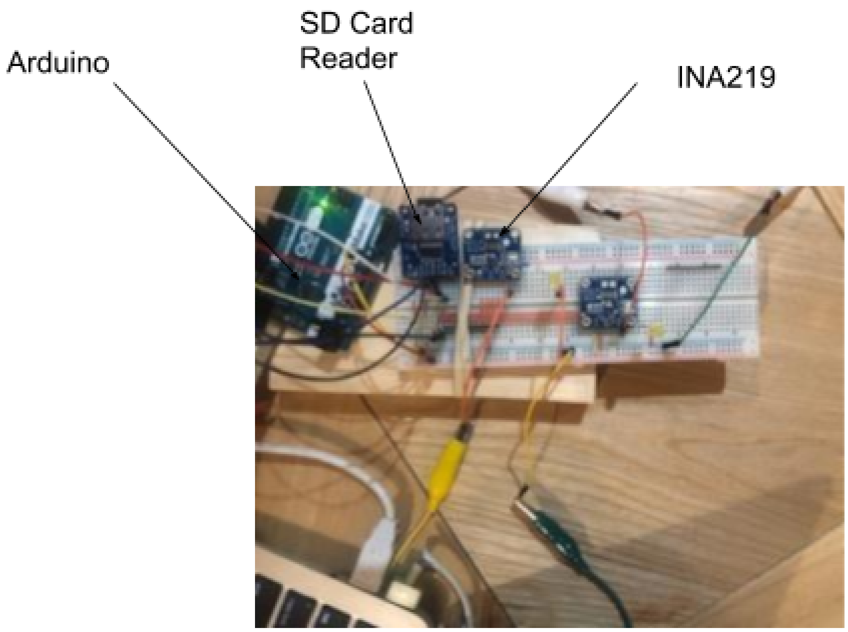

Fig 8. Measuring Circuit with Arduino

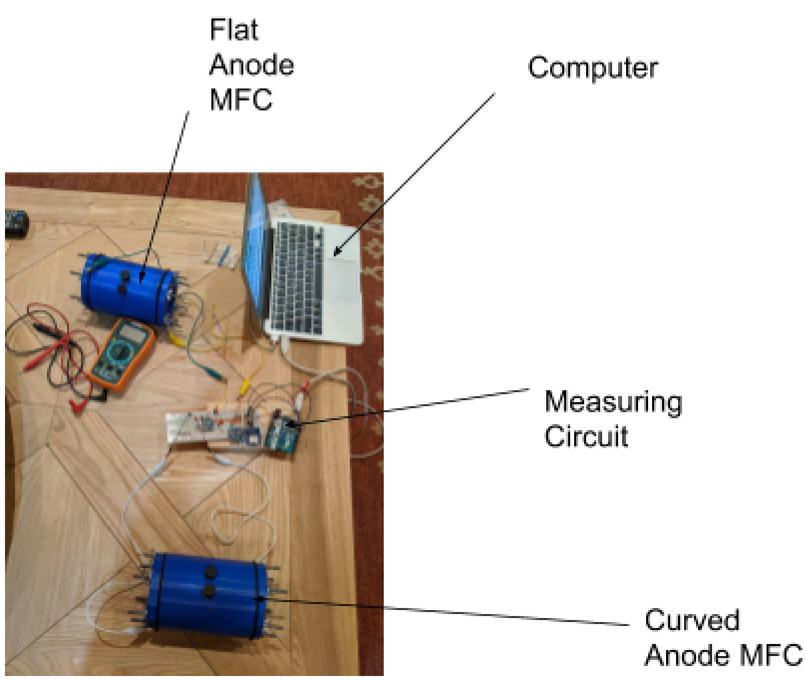

Fig 9. Final Experimental Setup

Procedure

1. Create four IPT files for the curved anode, normal anode, cathode, and chamber.
2. Model the curved anode.
    a. Extrude a 4" diameter circle 0.5" deep.
    b. Use the equation curve to model a cosine curve perpendicular to the extrusion.
    c. Copy and translate the curve up ¼" and connect both curves with a line.
    d. Extrude that shape 1.5".
    e. Extrude 6 0.25" holes on the square in a rectangular pattern.
    f. Create two small rectangular supports on either side of the cosine curve.
3. Model the chamber.
    a. Extrude a 4" diameter circle 4" deep.
    b. Extrude a 1.5" square hole through the chamber.
    c. Extrude 6 0.25" holes on the square in a rectangular pattern.
    d. Extrude a 0.1" deep circular depression on the cathode side with 2.5" diameter for the cathode.
    e. Extrude two 0.25" diameter holes for the stoppers.
4. Model the normal anode.
    a. Extrude a 4" diameter circle 0.5" deep.
    b. Extrude a 1.5" square out from the main part.
    c. Extrude 6 0.25" holes on the square in a rectangular pattern.
5. Model the cathode.
    a. Extrude a 4" square.

b. Extrude a 2.5” hole through the square.
c. Extrude 6 0.25” holes on the square in a rectangular pattern.

6. Convert all four IPT files to STL files.
7. Transfer them to the 3D printer using a USB drive.
8. Print two copies of the cathode, two chambers, one curved anode and one normal anode on the 3D printer.
9. Cut the carbon paper to the size of the normal anode and the curved anode.
10. Add hot glue to the normal anode and curved anode backings.
11. Place the titanium wires on the glue so it sticks out from the anodes.
12. Attach the cut carbon paper to the glue on the curved and normal anode.
13. Make the cathodes.
    a. Cut the Pt paper into a circular shape.
    b. Spray both sides with silicone spray.
    c. Let both cathodes sit for 24 hours.
14. Cut out 4 4” circles of gasket material.
15. Cut out 1.5” squares in the center of two of the gaskets.
16. Poke six holes in all 4 gasket circles corresponding with the holes in the cell.
17. Assemble the cells.
    a. Put the cathodes in the circular depression on both plastic cathode backings.
    b. Press the titanium wire on both cathodes.
    c. Put the gasket with the square hole on the cathode side and the other gasket on the anode side.

d. Insert the anode into the anode side and press the cathode to the cathode side of the chamber.
e. Make sure that the anode and cathode are snug and the gasket is tight.
f. Insert a threaded rod through the hole in the cell.
g. Using two wing nuts, tighten the rod.
h. Repeat steps a-g for all 6 holes on both cells
i. Fill both cells with water and pour the water out, measuring the volume of the water in a beaker.

18. Make the medium.
    a. Measure 1 liter of dechlorinated water.
    b. Add 3 BOD pillows to the water.
    c. Add 1.4 grams each of NaH_2PO_4 and Na_2HPO_4 into the medium.
    d. Stir the mixture.
    e. Store in the fridge.
19. Set up the measuring circuit.
    a. Plug the current sensors into the breadboard.
    b. Connect the SDA and SCL pins on the sensors to SDA and SCL on the Arduino using jumper wires.
    c. Connect the power and ground on the sensors to power and ground on the Arduino using jumper wires.
    d. Plug the SD card reader into the breadboard.
    e. Plug the SD card into the SD card reader.

f. Connect the SPI pins on the reader to the SPI pins on the Arduino using jumper wires. (MOSI, MISO, CS, SCK)
g. Connect power and ground on the reader to power and ground on the Arduino.
h. Connect two 1k ohm resistor from Vin- on both sensors to ground on the Arduino.
i. Attach the crocodile clip wires to the titanium wire sticking out of both cells.
j. Attach all crocodile clips to jumper wires.
k. Plug the anode jumper wire on both cells into Vin+ on the two current sensors.
l. Plug the cathode jumper wire on both cells into Arduino ground.
m. Write an Arduino sketch which gets the power reading from the sensors and writes it to a file every minute.

20. Collect the data.
    a. Travel to pond and use shovel to fill beaker with pond sludge.
    b. Put 55 ml of pond sludge into both cells once back at the lab.
    c. Fill the rest of the cells with medium and add .4 g of glucose to each cell.
    d. Close both cells using the stoppers.
    e. Plug the Arduino into the computer.
    f. Upload sketch and run for 24 hours.
    g. Copy data from SD card onto computer.
    h. Write C++ program to read file and get 24 regularly spaced readings from the file.
    i. Run program on both files and obtain 24 data points.

Data Tables

The independent variable is the anode design. The dependent variable is the power output.

Table 1: Raw Data for Power Output of a Curved Anode MFC and a Flat Anode MFC

Trial	**Flat Anode MFC (mW)**	**Curved Anode MFC (mW)**
1	0.37	0.26
2	0.39	0.17
3	0.37	0.26
4	0.41	0.34
5	0.45	0.30
6	0.40	0.21
7	0.40	0.26
8	0.36	0.22
9	0.36	0.35
10	0.45	0.31
11	0.50	0.31
12	0.45	0.40
13	0.45	0.31
14	0.32	0.26
15	0.50	0.22
16	0.50	0.35
17	0.45	0.26
18	0.44	0.31
19	0.57	0.35
20	0.52	0.30

21	0.43	0.26
22	0.51	0.16
23	0.36	0.32
24	0.39	0.37

Table 2: Summative Data Table for Power Output of a Curved Anode MFC and a Flat Anode MFC

	Flat anode (mW)	**Curved anode (mW)**
mean	0.43	0.29
Std. deviation	0.063	0.061
var	0.0039	0.00038
n	24	24

Graphs

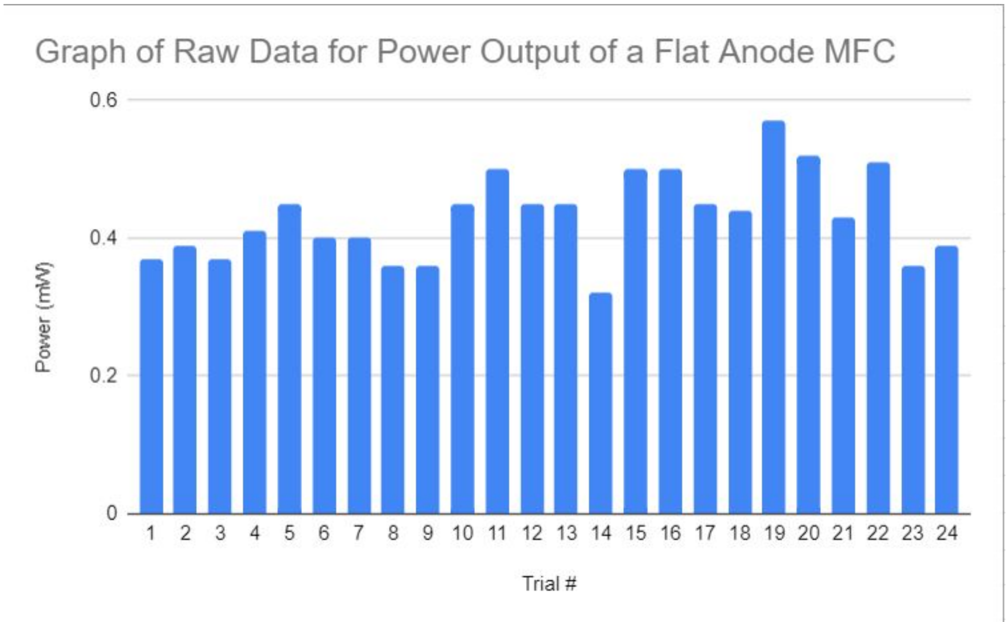

Fig 10. Raw Data Table Graph for Flat Anode

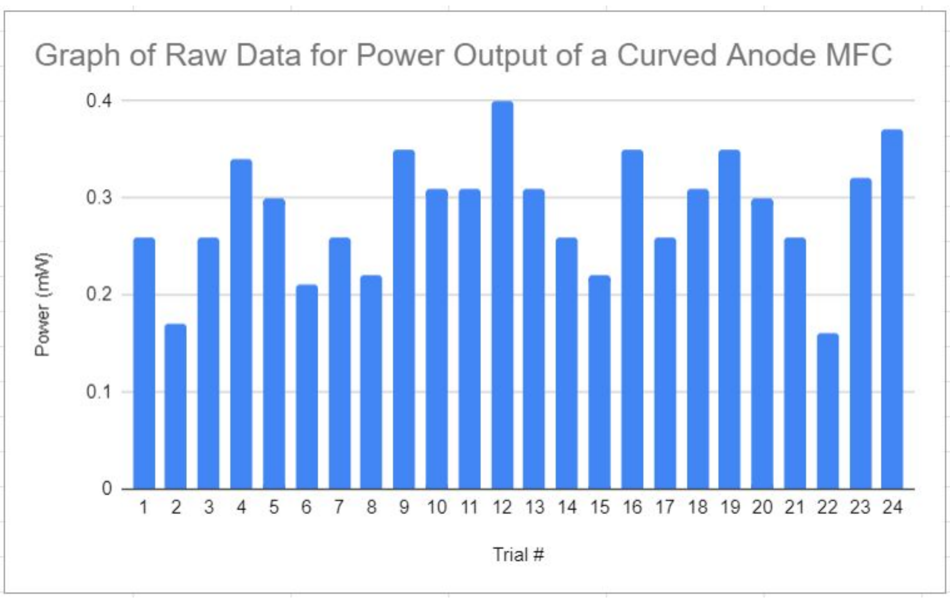

Fig 11. Raw Data Table Graph for Curved Anode

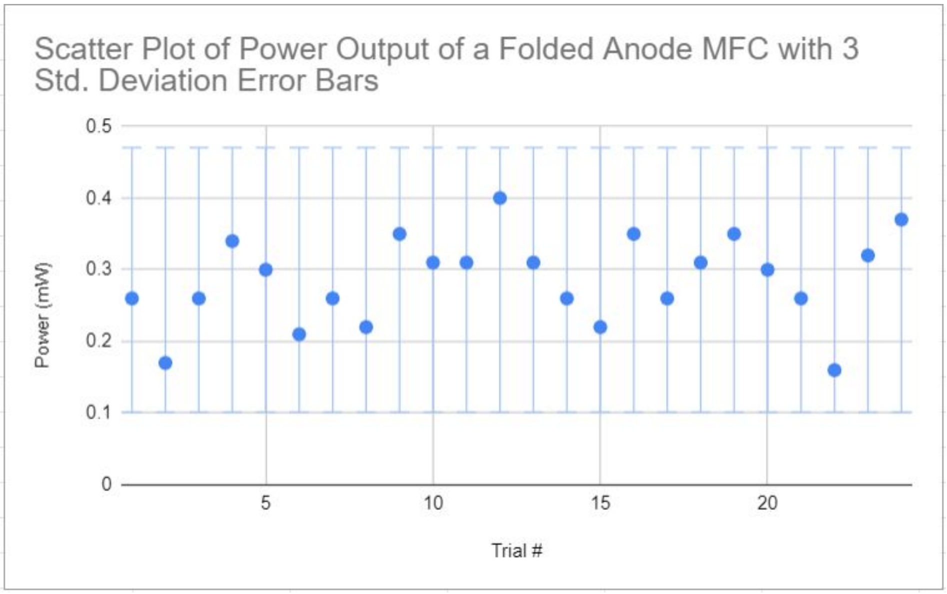

Fig 12. Scatter Plot for Folded Anode

There are no outliers in this group.

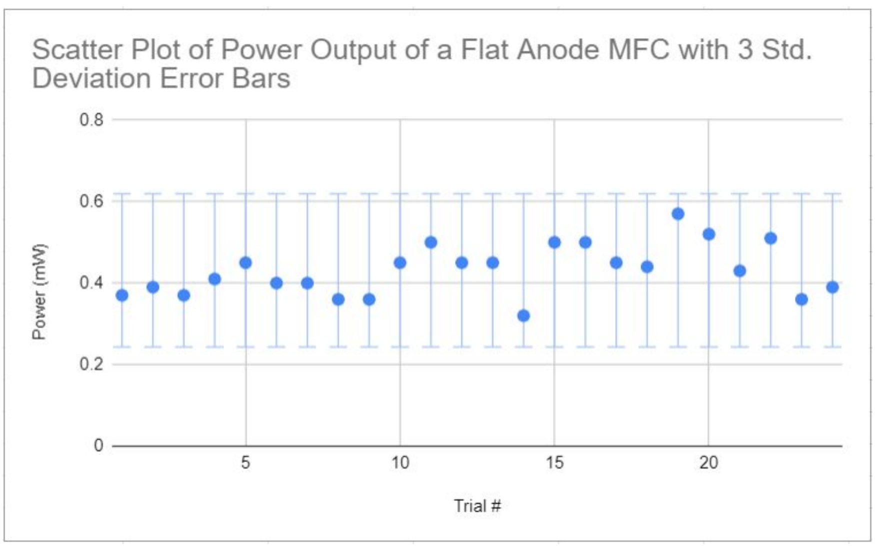

Fig 12. Scatter Plot for Flat Anode

There are no outliers in this group.

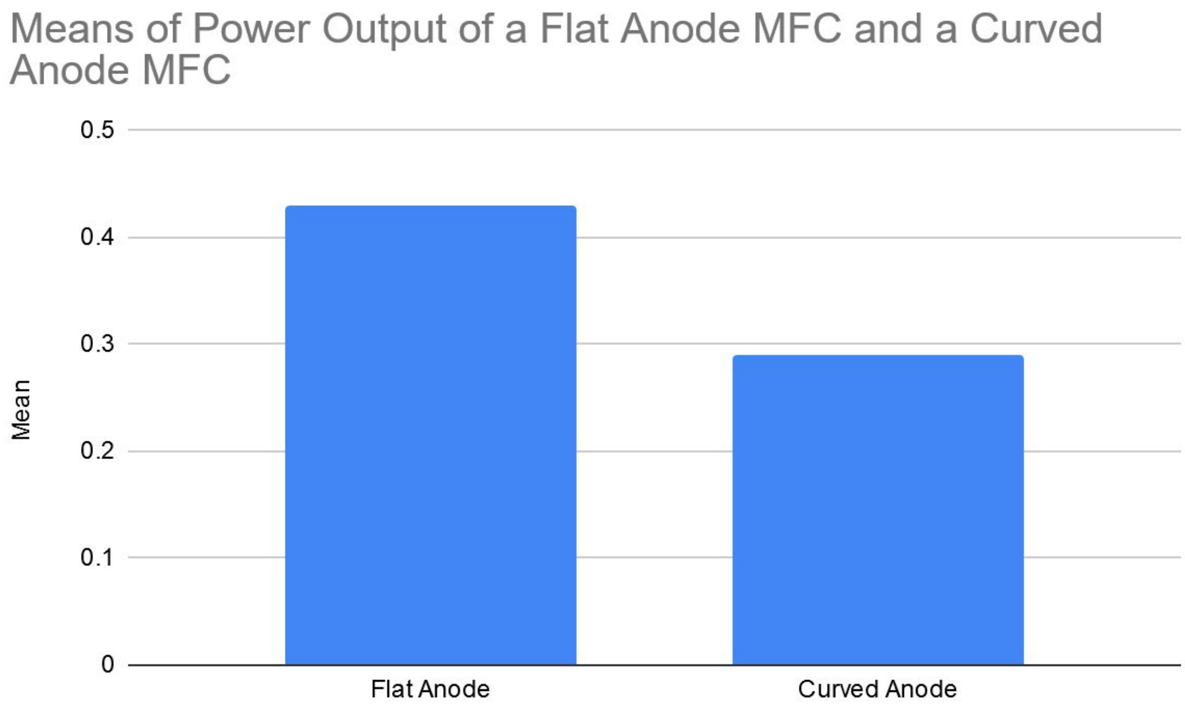

Fig 13. Mean Graph of MFC Power Outputs

Inferential Statistics

To obtain a p-value, a two-tailed independent t-test was used. A t-test is used to find the p-value for two sets of quantitative data. The p-value was compared to an alpha value or level of significance, which in this case is 0.05. Since there were only two levels of the independent variable in this experiment, an ANOVA test was not used. The test was two-tailed because a difference in both directions is being measured. The test was independent because the subjects in each group are not the same.

The p-value for this study is 0.0000000002.

Discussion of Statistical Results

Since the p-value is less than the level of significance, the null hypothesis is rejected. The alternate hypothesis is supported. The results show that there is a significant difference between the power output of a flat anode MFC and a curved anode MFC.

Discussion of Research Results

This study showed that there is a significant difference in the power output of a curved anode MFC and a flat anode MFC. However, the flat anode had a higher power output, contradicting the initial expectations of the study. This could be due to a multitude of reasons. The most likely explanation is a decrease in biofilm formation on the curved anode. Because the anode contained folds, it may have made it more difficult for the bacteria to form a uniform biofilm on the carbon paper. The lessening of biofilm formation could also be due to less contact between the sludge and the paper in the curved anode MFC.

Overall, this research provided some interesting insights into the inner workings of an MFC. While it is not possible to ascertain why the flat anode had a higher power output, it is still important to further test the effects of anode surface area on MFC power generation.

Suggestions for Further Study

There are many aspects of this study which could be expanded upon and improved. Firstly, the power output of the cells could be increased by using wastewater. Wastewater generally has more anaerobic species of bacteria and is easier to work with than pond sludge. Secondly, the cell could have been purged with nitrogen. Nitrogen purging would have removed all traces of oxygen, eliminating the possibility of aerobic respiration.

The change in anode design had an effect on the power generation of the MFCs. It caused a reduction in power production. As stated above in the discussion of the results, the way surface area was increased in this study may have made it more difficult for bacteria to form biofilms on the anode. To remedy this, surface area could be increased on a microscopic level. By using porous carbon paper or nanoparticles, the effective surface area and conductivity of the anode could be enhanced without harming biofilm formation. Another possibility is to use a 3-dimensional anode, where biofilms can form on all sides. While this study did not successfully increase the power output of an MFC, it can be used as a baseline to further improve anode design and bring MFCs closer to potential commercial applications.

Works Cited

Ada, Lady. "Adafruit INA219 Current Sensor Breakout." *Adafruit Learning System*, 26 Oct. 2012, learn.adafruit.com/adafruit-ina219-current-sensor-breakout/wiring.

This source provided the wiring diagrams and usage instructions for the INA219. It served as a basis for the creation of the circuit and also helped in debugging it when it was not working. It also explained the differences in various current and voltage measuring techniques, and which ones were best for certain applications.

Das, S., et al. "Impact of Electrode Surface/Volume Ratio on Li-Ion Battery Performance." *COMSOL*, www.comsol.com/paper/download/194393/hui_paper.pdf.

This paper provided the basis for the rationale. It explained the necessity for high surface area anodes and their advantages in power generation. This source gave methods on how to increase surface area as well.

Kim, Hyung Joo, et al. "A Mediator-Less Microbial Fuel Cell Using a Metal Reducing Bacterium, Shewanella Putrefaciens." *Enzyme and Microbial Technology*, vol. 30, no. 2, 2002, pp. 145–152., doi:10.1016/s0141-0229(01)00478-1.

This source provided information about the cathode that should be used. It explained the use of a passive air transfer cathode, which is used as a half reaction in the cell to complete a circuit.

Liu, Hong, and Bruce E. Logan. "Electricity Generation Using an Air-Cathode Single Chamber Microbial Fuel Cell in the Presence and Absence of a Proton Exchange Membrane." *Environmental Science & Technology*, vol. 38, no. 14, 2004, pp. 4040–4046., doi:10.1021/es0499344.

This source provided detail on the use of a PEM. It said that a fuel cell does not need a PEM, and in fact PEMs are not useful for maximal power output.

Sure, Sandeep, et al. “Microbial Nanowires: an Electrifying Tale.” *Microbiology*, vol. 162, no. 12, 2016, pp. 2017–2028., doi:10.1099/mic.0.000382.

This source provided preliminary research about exoelectrogenic bacteria. It discussed various methods for microbial electron extraction and various bacteria which can use metal as a final electron acceptor in cellular respiration.

Zielke, Eric A. “Design of a Single Chamber Microbial Fuel Cell.” *Penn Engineering*, 15 Dec. 2015, www.engr.psu.edu/ce/enve/logan/bioenergy/pdf/Engr_499_final_zielke.pdf.

This source provided the details on how to build a microbial fuel cell. It contained valuable information about parts and methods commonly used in assembly. In addition, it talked about the interactions between the cathode and anode in a cell.