The performance of varying PTFE coated fabric cloth on electricity production using synthetic wastewater with aid of activated carbon air-cathode.

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DEDICATION

This report is dedicated to my fellow post-graduate students, and all inspiring students who are working towards their M-Tech degree and my lecturers who taught me that the best kind of knowledge to have is that which is learned for its own sake and that the largest task can be accomplished if it is done one step at a time, I thank all.

Finally I would like to express my sincere thanks to my friends and family. They have made the last few years, and this project, the largest and most difficult undertaking of my life thus far, among the most enjoyable times I can remember. While I am glad to be completing my thesis, I will be hard-pressed to find anything like the sense of community and genuine affection for my surroundings that I have had at the University of Johannesburg in my work in the future. I thank all immensely.

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ABSTRACT

Microbial fuel cell is the energy harvesting technology being studied; this technology concerns various substrates, microbes and wastewater into electrical energy by the catalytic reaction of micro-organisms. The thesis of the project research seeks to establish a comparison in the performance of biochemical properties for microbial fuel cells using synthetic wastewater and activated carbon. The cathode electrode used was a stainless steel pressed with activated carbon and was sectioned to a surface area of 36cm^2 same with the proton exchange membrane and the carbon cloths were also sectioned at 36cm^2. The experimental set-up consisted of a double chamber membrane which consisted of the anode and air-cathode chamber. The anode and air-cathode chamber were immersed in the open water bath regulated at a temperature of 35^{o}C. On the start-up, the anode chamber was filled with 280ml of synthetic wastewater which was mixed and prepared in the lab to reach the ideal COD levels which meet the raw domestic wastewater COD levels and the air-cathode was filled with 8L of tap water. The anode chamber after every experiment was changed and fitted with a new and different carbon cloth coating, whereby the cathode chamber had to be changed with an addition of the pulverized activated carbon.

The 50% PTFE coated carbon cloth is more efficient in generating power than the other which were compared to in the experiment; however the performance of individual carbon cloths varies significantly with the type or percentage of coating added and this directly affects the overall performance of the MFC, and this was highly aided with the addition of the activated carbon.

An air-cathode with activated carbon with different particle sizes which was embedded on a stainless steel mesh. Microbial fuel cell (MFC) containing synthetic wastewater was constructed and compared to different types of carbon coated polytetrafluroethylene (PTFEs). The synthetic wastewater contained in MFCs was investigated and together with the aid of activated carbon which was pulverized to different sizes for oxygen removal. The synthetic wastewater MFC had a power output of 86.80mW/m2, compared to 17.47mW/m2 for the domestic wastewater. The limiting current density is 0.0347mA/m2 for the activated carbon in synthetic wastewater compared to 0.0046mA/m2 for domestic wastewater without an

activated carbon catalyser, despite an increase in internal resistance between the anode and cathode chamber which included an ion exchange membrane in the MFC system. Analysis of metabolites has shown that activated carbon is likely to have positively affected current production by the use of pulverized carbon, and the removal of oxygen is responsible for the increased current density in synthetic wastewater.

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LIST OF ABBREVIATIONS

PTFE:	Polytetrafluroethylene
MFC:	Microbial fuel cell
PEM:	Proton exchange membrane
CEM:	Cathode exchange membrane
RVC:	Reticulated vitreous carbon
PMS:	Power management system
COD:	Chemical oxygen demand
OCV:	Open circuit voltage
ΔG_{cell}:	Gibbs Free Energy of net cell reaction
I:	Current
R:	Resistance
$R_{internal}$:	Internal resistance
V:	Voltage
NADH:	Nicotinamide adenine dinucleotide

CHAPTER 1

INTRODUCTION

1.1 Background

Power shortage in many countries around the world is a major problem especially with the advancement of technology. Countries like South Africa which has only one company (Eskom) which generates the country's electricity is trying different methods on improving the power generation output. Eskoms nuclear plant like the Koeberg Nuclear Power Station located in Cape Town (South Africa) are causing environmental problems. Hence, new technical development like Microbial fuel cells (MFC) is being researched to improve power generation.

The general principal of an MFC (microbial fuel cell) is to convert chemical energy from using bacteria to break down organic compounds into electrical energy through reactions of micro-organisms conditions which are anaerobic (Suzuki et al, 1978). An MFC configuration is composed of an anode and a cathode compartments which are separated by a proton exchange membrane (PEM) or cathode exchange membrane (CEM). Micro-bacteria in the anode are oxidized and therefore produce electrons and protons in the system. The produced electrons move to the cathode through an external circuit (Oh and Logan, 2006), while the protons move through the PEM into the cathode compartment, therefore the potential difference between the two compartments results in power generation (electricity). An electron acceptor such as oxygen produces water, (Oh and Logan, 2006) by reducing protons and electrons in the system also assisting in power generation. The research project regulated the performance of different anode coating on electricity production in microbial fuel cells (MFC) using raw domestic waste water.

1.1.1 Fuel Cells

Microbial fuel cells (MFCs) are electrochemical devices which convert chemical energy into electrical energy. They are very much similar to other fuel cells but the main difference is that they use bacteria for power production. Typical well know fuel cells have an electrode, an anode and a cathode chamber which is used in the MFC system design, so an MFC has two main chambers an anode and a cathode. During the continuation of this thesis they will elaborate more on each chamber. A typical reaction in an MFC will be seen or noticed by an electron donor which is formed on the anode chamber, usually protons and electrons which is oxidized on the surface of the anode. This oxidization process leads to the formation of protons and other cations in the system. The electrons will be reduced in the anode due to oxidation, thus being explained as oxidation is a loss of electrons at the anode and this reduction causes a purification method of reducing the COD levels in wastewater and creates a current in the circuit which produces electricity. The other cations such as protons from the anode chamber will pass through a selective membrane usually called a proton exchange membrane (PEM). To the cathode side of the system. The main reason for this to happen is because the fuel cells system needs to equalize the charge transferred by the electrons. In some fuel cells, a transfer of anionic ions from the cathode chamber may be transferred to the anode.

In order for electrical energy to be harvested from the fuel cell system, there needs to be an introduction of an external load between the anode and cathode chamber so the electrons can be harvested. Usually catalysts is required on either side or both sides of the two chambers (anode and/or cathode). This catalytic reaction will allow electron donors from the anode to be oxidized while allowing a reduction of cathodic acceptors in the cathode chamber.

Below is a typical fuel cell system being show in fig. 1.1.1.1 which has the presence of a selective membrane between the anode and cathode chamber. The process is explained initially from the anode chamber where hydrogen is split into protons and electrons, whereby these protons pass through a selective membrane (PEM), while the electrons in the anode chamber travel through an external circuit and with the potential difference between the anode and cathode electrical energy can be harvested. The protons which have passed through the selective membrane will now travel into the cathode chamber where they react with oxygen which is open to the air to form water. Both the anode and cathode surface areas can be enhanced with a catalytic surface like platinum to increase the fuel cells power production.

From the above reaction to harvest electrical energy they can note that two half reactions have taken place. The overall reaction taking place in a fuel cell is the same as the combustion of hydrogen gas which gives out the same amount of energy. The first half reaction takes place in the anode chamber where hydrogen is oxidized to form electrons and protons in the system. And, the second half reaction takes place in the cathode chamber through the reduction of oxygen in the system to form water from the reaction of protons and oxygen. The only difference is that a fuel cell harvests electrical energy and not heat. So, the loading taking place between the anode and cathode allows us to generate electricity from wastewater. Below are the reactions (half-cell reactions) which are taking place in both the anode and cathode chamber:

Anode Reaction: $2H_2 \rightarrow 4H^+ + 4e^-$

Cathode Reaction: $4H^+ + 4e^- + O_2 \rightarrow 2H_2O$

Cell Reaction: $2H_2 + O_2 \rightarrow 2H_2O$ $\Delta G_{cell} = -474.4$ kJ/mol

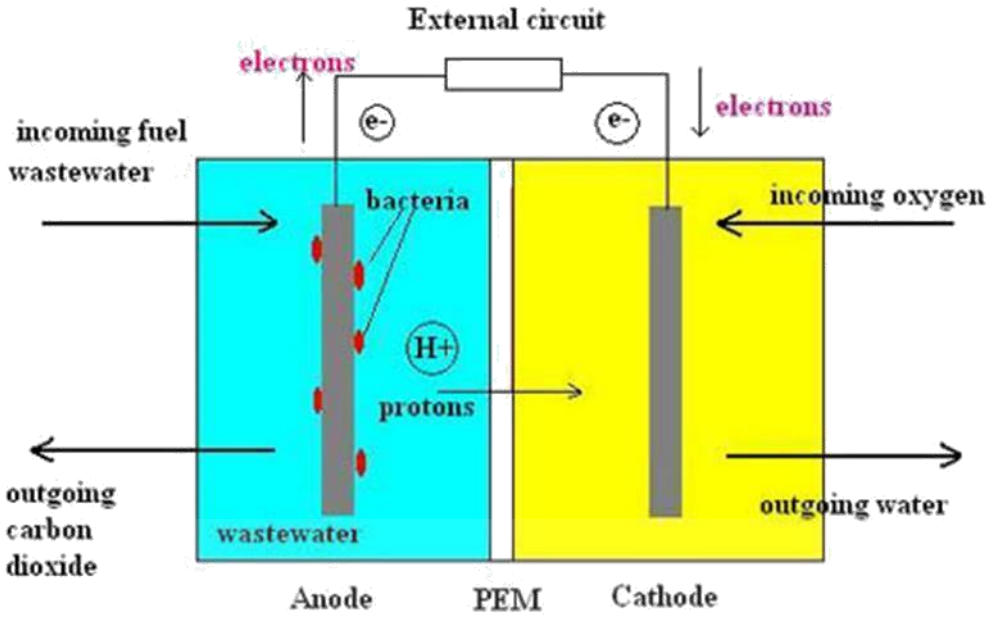


Fig. 1.1.1.1 *– Typical fuel cell operation for a microbial fuel cell.*

Fuel cell systems have their own characterizations for reading and finding certain information on the performance of the system. There are two main curves which they pay attention to. The power and operating curves, which ideally show how the voltage and power produced varies with respect to the amount of current in the system. These two main curves should be paid considerable amount of attention as they tell us give important properties of the system such as the maximum power produced, the most optimal external resistance needed and operating voltage required in the system. Keeping in mind that there can be external resistance in the system between the anode and cathode which will be discussed further in the following chapter, which is one of the important properties they obtain from the power and operating curves. The main characteristic of the operating curve is best shown as a sigmoid shape. The shape of this curve shows two distinct levels, initially at open current when there is no current passing through the system, it is easily noticed that there is a maximum level of the systems potential. But as there is an increase they can note that there is a decrease in activation loss and ohmic loss in the system for the initial first portion of the curve. In the initial portion of the curve which is non-linear, decrease in activation loss is caused at low current densities and the main cause of this is due to the fact that there is slow kinetics is happening in the

anode chamber but mostly occurs at the cathode chamber. The decrease in activation losses due to the kinetics are more concentrated at low current densities. All of this is caused by the activation energy which is needed to push the forward reaction and increase current densities. The straight-line segment in the curves mainly shows the decrease in potential difference in the system this is all because of the ohmic losses which is taking place in the MFC system, the second loss is resistive loss due to the electrodes which are situated in both the anode and cathode chamber also the PEM has an effect on resistivity. But even though there is a decrease in activation in the overall system this inversely shows an increase in current densities. The maximum MFC system internal resistance can be shown by using ohms law (V=IR), the law is used on the linear portion of the curve.

Looking at the last portion of the curve, it is easily noticed that there is a decrease in potential difference in the system while the current increases. This portion also shows the depreciation of the mass transfer in the whole system, it is further noted as the transfer limited region of the curve. This decrease in loss is due to a diffusive limit which has been reached by electrically active species. The main decrease can be explained further by indications of either the electrons donors or acceptors cannot be able to diffuse fast enough on the electrode or are charge neutralizing ion cannot travel fast enough through the electrolyte in the system. The emphasis and indication that any MFC system has a mass limiting factor which results in a current density limit. Even if the external resistance attached between the anode and cathode is changed, this will not lead to an increase in current and will obtain potential losses due to the limited amount of electrically active species in an MFC system.

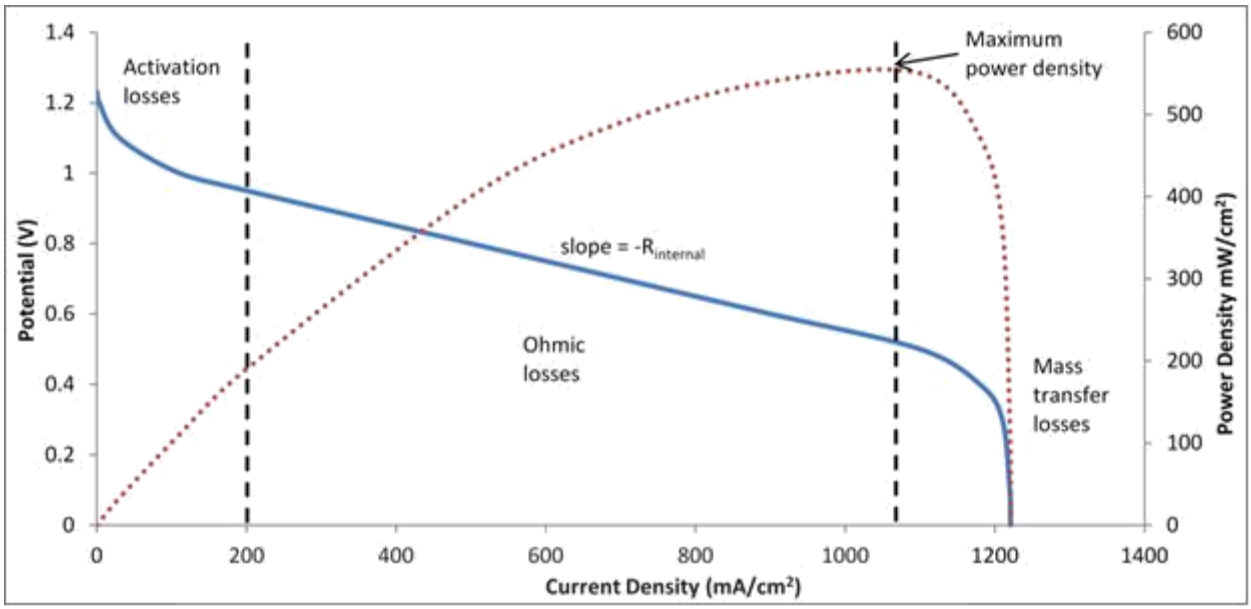


Fig. 1.1.1.2 *– Operating curve (---) and power curve (ooo) for a typical fuel cell.*

1.1.2 Microbial Fuel Cells

An MFC system uses the same process as a typical fuel cell. The only major difference is that in an MFC the anode reduction is part of a bacterial metabolism. The bacteria metabolism is part of an anodic catalyst for the oxidation reaction of the electron donor. The bacteria are not limited to any substrate which the bacteria are consuming but it is often glucose or acetate. And on the cathode chamber there can be a wide range of electron acceptors which can be used but the easiest and mostly used electron acceptor is oxygen. In this study will be operating with an open air-cathode, hence utilizing oxygen as our electron acceptor (Du et al, 2007). Another electron acceptor which is may be used is ferricyanide, this is usually used when the cathode chamber is not that of interest to anyone looking to research in MFCs, the main reason is because it has very high potential and is properties allow for an excellent reagent which has no limitation to the MFC system, hence researcher will be able to view and investigate on the anode chamber which will be of interest when the use of ferricyanide is chosen as the electron acceptor (Du et al, 2007). For every advantage there is a disadvantage when working with ferricyanide, the main problem with working

with this type of electron acceptor is that, ferricyanide is not cheap and cost effective in an MFC system and has potential to be leaked and be toxic outside the anode chamber if it is not well secured. Ferricyanide is a toxic compound and may affect the electrically active species in the anode chamber, and lastly another disturbing problem with ferricyanide is the disposing of the toxic compound, which may lead to waste be a potential threat to anyone coming in contact with the substance, as it is not easily disposable (B.E. Logan, 2010).

Hence, for the provided reason above, oxygen is ideal to be used in an MFC system in the cathode chamber (Kim et al, 2007). This system is similar to a hydrogen fuel cells which is used to reduce any costs in cleaning the oxygen, therefore ambient air is preferable. Below is a view of an air-cathode MFC system which can be seen in fig 1.1.2.1.

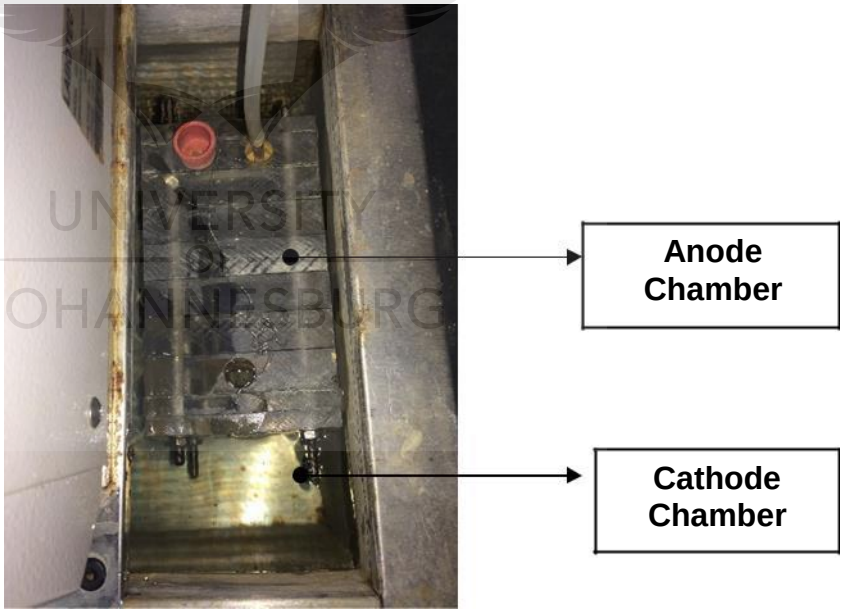


Fig. 1.1.2.1 *– Typical fuel cell operation for a single-chamber air cathode microbial fuel cell, and activated air cathode.*

An MFC system of an air-cathode chamber does not always contain a selective membrane a Proton exchange membrane (PEM). Usually what happens in a hydrogen fuel cell is that both the anode and cathode chamber are induced with gases, hence a physical selective material is

needed to avoid the contents in both the chambers to mix and create a potential difference in the system. The system is not only limited to a PEM but any selective material which allows ionic conductivity for the internal circuit can be used (H. Liu and B.E. Logan, 2004). MFC systems using an air-cathode the mediums in the anode and cathode can act as electrolytes between them and in this case a PEM will not be necessary to be used in the system and is therefore removed. This brings forth an advantage to the whole system as the internal resistance is reduced and the protons move faster through the medium (culture medium) then moving through a PEM. But the down fall for not using a PEM is that the system will experience an increase in oxygen diffusion into the whole MFC system (Kim et al, 2007).

The main characterization of any MFC system is the power and operating curves, which is still the same for any typical fuel cell. These curves provide the same vital information and also obtain the same shape as discussed previously. But, there is one huge difference when they pay closer attention to the mass transfer region. This region can be explained using the information from the anodic bacteria, because these bacteria will have a limitation in their metabolic rate of respiration rather than diffusional limitation, regardless of all the differences in the system one will obtain the same power production (Rabaey et al, 2005). Power and operating curves are not the only main measure of the efficiency of an MFC system. One of the other important measures which need to be taken into consideration is the columbic efficiency of the system. Columbic efficiency is the measure of the yield on electron and is explained as; it is the number of electrons harvested by the system and the number of available electrons when fully oxidized by any food source or substrate (Ieropoulos et al, 2005).

1.1.3 Bacterial Metabolism

Bacteria in an MFC system act as catalysts only in the anode chamber this happens as discussed previously by an anode reduction by bacterial substrates either being glucose or acetate. The process of oxidation phosphorylation allows electrons to form and to be produced in the bacteria final steps of the electron transfer chain. During the course of metabolic oxidation, the electrons are stored in shuttle molecules such as NADH. The produced shuttle molecules will allow these electrons to go a past a number of membranes bound proteins. A conformational change will cause protons to be pumped through a membrane; the resultant for this will be to create a charge for the system and diffusional gradients throughout the membrane. This will give us the last overall proton motive force which can be utilized in the air-cathode chamber. The use of activated carbon will assist with the motion of proton motive forces. In this particular research activated carbon has been pressed on a stainless-steel mesh. This chemical potential gradient is exploited by bacteria to assist in the power production in the system. Below is a schematic diagram of activated carbon pressed to stainless steel mesh

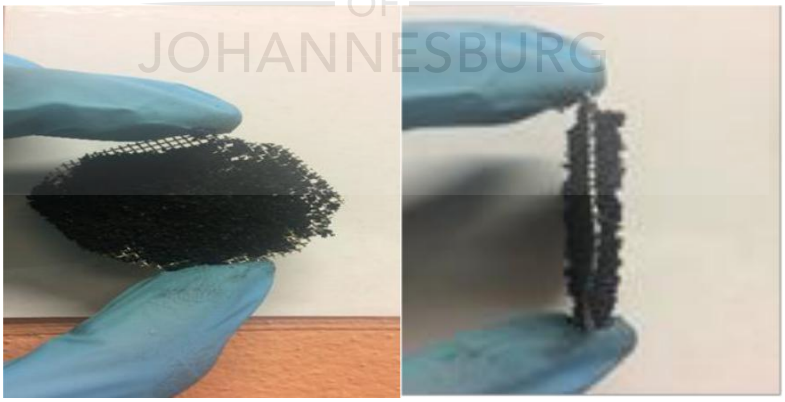


Fig. 1.1.3.1 – *Activated carbon pressed to stainless steel mesh. (Schematic).*

In the figure above, oxygen as the electron acceptor is typically called the terminal electron acceptor to the electrons once they have passed through the electron transfer chain. This process can only be reacted in the aerobic

organisms. But this does not apply for anaerobic organisms this is because the organisms are not capable of oxidative (Reguera et al, 2005). Other bacteria such as electrically active species are able to evolve and form electron transfer chains which enable them to use other molecules with the aid of oxygen as the main terminal electron acceptor (Cologgi et al, 2011). MFC systems uses these electrons which are most capable of reducing any amount of high oxidation state metals to a lower oxidation state, and this is done by transferring electrons (Butler et al, 2010). These metals are usually present as solid oxides in sediment, and the bacteria have evolved methods for reducing them extracellularly (Gorby et al, 2006). The whole process can and may be accomplished by inducing a mediator in the system which will act as a transporting medium for the electrons secreted by the organism and also in turn this can be achieved by other organisms growing in groups with them (Marsili et al, 2008). There is another method which can be used either by allowing the electrons to make direct contact with the outer membrane cytochromes, the extent of the range at which the electron can be transferred is due to conductive proteins (M. Brownlee, 2001).

The main and critical consideration is suitable potential difference which will occur between the bacteria and external terminal acceptor. Respiring on fuel cell anode chamber is caused by these bacteria with mechanisms for extracellular transfer, this will only occur provided that the potential is high enough from the anode chamber to the cathode and also taking into consideration that the circuit resistivity is not too large in the system.

1.1.4 Fuel Cell Chemistry

During the fuel cell chemistry, the most preferred substrate is acetate and hence the reaction is used below as an example for an MFC system chemistry. The half-cell reactions for an electrically active species respiring with acetate as the main electron donor and an air-cathode in an MFC system is given below:

Anode Reaction: $CH3COO^- + H^+ + 2H2O \rightarrow 2CO2 + 8H^+ + 8\ e-$

Cathode Reaction: $8H^+ + 8e^- + 2O2 \rightarrow 4H2O$

Cell Reaction: $CH3COO^- + H^+ + 2O2 \rightarrow 2CO2 + 2H2O$
ΔG_{cell}= -842.2 kJ/mol (C.L. Yaws, 1999)

A MFC system which is respiring with a substrate such as acetate, given the Gibbs free energy of -842kJ/mol it can be noted that the maximum possible voltage for an MFC with an oxygen air-cathode system is in the range of 0.5 – 0.8 V only for an open circuit without any external resistance being applied between the anode and cathode (Nevin et al, 2008). This divergence mentioned above is mainly due to the losses during metabolism and the amount of energy which has been used by the bacteria, and this energy usage cannot be avoided by any means because the electrically active species need to derive any energy gain from the anode chamber to allow a forward reaction. The above formulas are in assumption of a pure oxygen air-cathode system, and are accompanied by an activity of 1 for all species present. Regardless whether if the system is adjusted to reach the acetate concentrations and pH levels, this will bring about difficulties to make an accurate prediction, this difficulty is due to the differenced in intracellular acetate and extracellular acetate concentrations because intracellular concentrations are the most important and are difficult to measure.

1.2 Technical development

The study of power generation from microbial fuel cells is still in optimization due to the fact that there is a moderately low production of power generation from synthetic wastewater using MFCs. The research project will regulate the performance of different anode coating on electricity production in microbial fuel cells (MFC) using synthetic waste water.

1.2.1 MFC Limitations

All fuel cell systems have their limitations, for researcher in the fuel cell space to improve on the MFC technology, it is advised and important that they know and understand the limitations the technology has. The main limitations to MFC technologies is the low power density when comparing it to other fuel cell technologies, currently the current status of portable energy density is 7 – 30kW/m^3 (Spendelow et al, 2011).

Currently at the moment the highest recorded power density is in the range of 2 – 2.15 kW/m^3, and this is only taking into consideration that they are dealing with the anode chamber volume and not including the cathode chamber in the system. MFC systems have a significantly high amount of large footprint and hence they may not be implemented on a small scale or be used in households due to their large footprints, but there are other fuel cells such as hydrogen fuel cells which can be implemented on a smaller scale depending in their usage. The only implementation of an MFC system is that in the marine industry where the marine sediments are used for power production in MFC systems and this is highly used in temperature probes which do not require too much power to be used.

One of the main principal limitations to the MFC technology is the amount of cost. Usually MFC research in the lab consists of some expensive materials being used in the anode chamber, cathode chamber and the selective membranes which are used for electron transfer. Materials such as carbon

cloth anodes, proton exchange membranes and catalysts in the cathode chamber are quite expensive especially looking at platinum catalysers for the cathode chamber. The materials mentioned above are not expensive if it had to be singled out individually, the expenses in the technology comes from constructing these materials needed for power generation in stacks of series and parallel to each other, hence more material is needed and thus an increase in expenses to obtain a reasonable amount of power production. Hence, the stacking costs for these components become expensive and that is why other power generation methods are being favoured compared to MFCs. While at the same time the very same used materials can be used and constructed to have more power production for other methods. For researchers to take advantage of the MFC system they need to find the most effective materials which will produce the greatest possible power production in the system, which will reduce costs. Another advantage to this system is that MFC systems is that the feedstock in the anode chamber does not require any further purification both on the anode and cathode chamber but mainly on the anode side of the system. Captivating into consideration that the large amounts of wastewater feedstock will result in revenue because electricity will be generated and the feedstock will be purified in the process. Taking advantage of reducing costs from revenues being utilized by treating the wastewater and obviously power production. From the above statements above revenue, it is quite evident that an MFC system will deal with large amount of wastewater in order to take advantage of any cost savings with the ramp-up of the MFC technology thus in turn will result in increased revenue for treating large quantities of water.

Oxygen diffusion is another limitation in the air-cathode chamber of an MFC system. Air-cathode chamber will be further discussed in this study. Oxygen as a limitation has two ways in the system (Lin et al, 2004). Initially oxygen has the ability to raise the anode potential in the system but at the same time reduce the overall cell potential (Oh et al, 2009).

And electrically active species are affected by oxygen in a bad manner as oxygen is toxic to these electrogens, a small amount of oxygen can slow down the metabolism of the system hence causing a decrease in MFC power density due to bypass in the anode reduction (Nevin et al, 2011). MFC systems can be able to maintain an anaerobic condition but this will only work in a lab scale and not on a large scale. The reason for this is because an addition of nitrogen gas can be added depending of the volume of the anode chamber and the type of electrically active species which are present as the culture medium in the system. An addition of nitrogen in larger scales will consume more energy than the MFC system can produce as power, hence its only ideal to be used in the lab (Liu et al, 2005). The distance between the anode and cathode is also another limitation in the system. The greater distance between the two chambers the more internal resistance the system will have. Therefore, in order to reduce any internal resistance, the distance between the anode and cathode chamber should be reduced (M.M. Ghangrekar and V.B. Shinde, 2007). Other methods are needed to maintain an anaerobic condition in order for the implementation of this technology. This indeed means that the sensitivity of the system is based on oxygen and the electrically active species in the culture medium of the system. Researcher now have to take into consideration what would happen if there was a leakage in the system and how this will be handled. A method of maintaining this is Sparging which is a technique used to sprinkle water on the anode chamber to allow efficient amount of oxygen back into the anode chamber. But this method of maintenance has a disadvantage of causing repeated agitation on the chamber which will cause a biofilm to grow. The growth of the biofilm results in higher current densities and therefore any form of agitation on the anode chamber is not required.

The last but not least limitation in an MFC system is the type of substrate that the electrically active species can consume. Usually as mentioned previously that bacteria consume and use up fermentation products such as glucose, acetate, and lactate, which are mainly found in a variety of food source used for fermentation processes organically and inorganically.

These electrically active bacteria are capable to consuming simple and complex substrates. But the advantage with this process is that even the most complex substrates which are not easily metabolized can be beneficial in power production of the system. Usually these beneficial complex substrates can and may be broken-down by different bacteria which are electrically active species and will reduce the power production in the system. These bacteria which are not electrically active will lead to a competition with those that can breakdown complex substrates to produce power. Hence, it is very important to understand the bacterium which is available in the culture medium and how they perform and interact with each other in an MFC system.

1.2.2 Project Rationale

Power shortage in many countries around the world is a major problem especially with the advancement of technology. Countries like South Africa which has only one company (Eskom) which generates the country's electricity is trying different methods on improving the power generation output. Eskoms nuclear plant like the Koeberg Nuclear Power Station located in Cape Town (South Africa) are causing environmental problems. Hence, new technical development like Microbial fuel cells (MFC) is being researched to improve power generation. Most wastewater treatment plants in South Africa are in debt because they consume more electricity than any other government utility. MFC systems may be implemented in several engineering fields which are a global concern such as mentioned above wastewater treatment plants. Currently climate change requires climate action to be taken, hence alternative and clean sources of energy are being research and used, and this is growing exponentially. Climate action puts an emphasis on MFC technology which is ideally since the human population is growing meaning more waste and more energy will be required.

The influent process in the wastewater treatment plant which is the separation of solids waste from the water consumes more energy for these treatment plants, not only that but also the treatment and handling of the separated solid waste (Centre for Sustainable Systems, 2011). MFC technology as discussed previously has the ability to treat wastewater while at the same time producing electricity. This single 1-stage process allows the recovery of some of the power put into the process, because this reduces the efforts of separating the waste as most of the waste is treated in the water itself. A better understanding will be highly essential and important in the sustainable energy movement of clean energy sources, especially in the worsening energy crisis. An achievement of MFC will provide a triple bottom sustainability development of social benefit, environmental benefit, and economic benefit. Micro-organisms have been utilized to treat domestic wastewater. The main problem at the moment is finding a link addition incorporating power production in the system.

In order to have a better understanding of how MFC systems work which will be used in wastewater treatment plants, its efficient to understand how both the anode and cathode optimization will improve the system and also an understanding of the electrically active species interact with each other. This study seeks to establish the relationship between different PTFEs which are coated at different quantities and how activated carbon will aid the air-cathode chamber for the overall system, whether there will be positive or negative results in the MFC system. In addition to the system a proton exchange membrane will be used in the aid of proton transfer from the anode chamber to the cathode chamber for the system. All these components will be stacked together. Synthetic wastewater will be the culture medium used in the anode chamber volume which was prepared using OECD/OCDE guidelines and have the same COD levels as domestic wastewater.

1.3 Research objectives

The principal aim of this project is to create an optimized air-cathode with the aid of activated carbon on the air-cathode chamber to have a better understanding on how power production will be affected with the use of a catalyse such as activated carbon. This optimization looks to also reduce the limitations which were mentioned in the previous section. The main hypothesis of this project is in creating a system which will be beneficial to the amount of power produced, hence the use of synthetic wastewater.

Firstly, using the OECD/OCDE guidelines synthetic wastewater is used which was measured to have the same standard as raw domestic wastewater. This synthetic wastewater was prepared using meat extract and urea which are the main chemicals in the mixture with other chemicals which will be discussed in the following chapters. The advantage of the system is that a PEM is present and will decrease oxygen diffusion into the cell, but will also increase the internal resistance of the system.

Secondly, the use of activated carbon will enable the MFC to be more optimized and act as a catalyst in the cathode chamber, which will in turn enhance the reaction taking place in the cathode chamber and converting to electrical energy.

The objectives of this project are therefore as follows:

1) To determine the effect of temperature and pH on power generation.
2) To construct several MFCs that can be run in a reproducible manner for comparison between experiments.
3) To determine the effect of synthetic wastewater to on power generation.
4) To determine the effect of PTFEs at the anode compartment on power generation.
5) To determine the performance of the anode and cathode in power generation of MFCs.

6) To determine the performance of different coated anodes on power generation.
7) And to analyse the efficiency of activated carbon on an air-cathode.

1.4 Justification of research

The study of MFCs it is noted that the system produces quite low amounts of electricity. This project research is expected to give us more knowledge and understanding on how to conduct other experiments which will lead to the improvements in the technology of MFCs generating electricity from microbes. This will therefore reduce costs in the treatment of wastewater.

1.5 Scope of research

The research project will regulate the performance of different anode coating on electricity production in microbial fuel cells (MFC) using raw domestic wastewater and electricity production in microbial fuel cell (MFC) will be studied. All research and experiments will be conducted through the University of Johannesburg labs (Analytical chemistry labs, Chemical engineering labs and Metallurgical labs) and other outside resources.

1.6 Report outline

The report outline shown below gives a brief description of what will be discussed in the following chapters.

Chapter 2

This chapter gives intensive literature review of the overall study of the project. Detailed literature on the principal of fuel cells and the microbes in fuel cells will be discussed. The design of different microbial fuel cells is discussed in detail. Also literature on application of MFC in general is discussed in this section of the thesis.

Chapter 3

This chapter deals with the experimental methodology of the project. The analytical methods and experimental procedure are explained.

Chapter 4

This chapter gives intensive results and discussions of the overall study of the project. Detailed results are discussed using tables and graphs.

Chapter 5

This chapter deals with the overall conclusions and recommendations of the project.

CHAPTER 2

LITERATURE REVIEW

2.1 Principal of fuel cells

A great deal of literature has been undertaken to understand and investigate the different designs for microbial fuel cell systems, operating conditions and also including the construction of different MFC systems. All of this relevant literature review has been in preparation for this project and was helpful in understanding different components, different culture mediums in the system, experimental design and ideally power production. The most significant papers and research articles including further readings of the literature have been mentioned in this thesis. A further reading of other papers has been helpful in the experimental design of the project.

Microbial fuel cells (MFCs) are electrochemical devices that use the metabolic activity of microorganisms to oxidise fuels, generating current by direct or mediated electron transfer to electrodes. (Rabaey & Verstraete, 2005). The device comprises of an anode chamber, a cathode chamber, electrodes, proton exchange membrane and an external circuit. The MFC convert a biodegradable substrate directly into electricity. (Logan, 2008). The anode holds the bacteria and the organic material in an anaerobic environment. The cathode holds a conductive tap water solution in a double chamber type MFC or air if it is the single chamber. The bacteria generate protons and electrons as the organic substrate is being converted into energy. (Mansoorian et al, 2003). The electrons are transferred directly to the anode chamber and to the cathode electrode via a stainless-steel wire. Protons pass through the ion exchange membrane to the cathode chamber to produce water as a result of the reduction process which is in terms of

hydrogen transfer (Mansoorian et al, 2003). The bacteria grow in the anode, oxidising matter and releasing electrons as they break down the substrate. (Logan, 2008). The cathode is supplied with air or other inoculum to provide dissolved oxygen for the reaction of electrons via an external circuit, protons and oxygen at the cathode, completing the circuit and producing power. (Gaviria, 2011). Chemical energy is converted into electricity by the microbes which releases electrons and hydrogen ions which from water. (Suzuki et al, 1978). The oxygen is supplied in the cathode chamber by air or other oxygen source. The materials used in the electrodes significantly influence the overall efficiency.

2.2 Microbes in fuel cells

Bacteria (microbes) breakdown organic matter and release energy in the process. Bacterium like Exoelectrogens, “exo-“for exocellular and “electrogens” based on the ability to directly transfer electrons to a chemical or material that is not the immediate electron acceptor. (Fernández de Dios, 2013). Exoelectrogenic bacteria are the most suited to function within an MFC due to their ability to transport electrons outside of the cell. This type of bacterium is useful in mediator-less MFC, an MFC system which do not require a mediator to assist in electron transfer. (Du et al, 2007). These exoelectrogens can be sourced in a number of places, according to Du et al, they are found in soil, marine sediment, waste water, fresh water sediment and activated sludge, which are rich with these microorganisms. (Du et al, 2007). An interesting relationship is found between exoelectrogens and fungi in recent studies which potentially increases stability in electron transfer as fungi act as a natural organic mediator. This can be a significant step toward scaling up MFC systems as fungi and bacteria can be found naturally.

2.3 Microbial fuel cell design

Previously mentioned in the last section, it has been noted that the cathode typically uses oxygen and/or ferricyanide as an electron acceptor (B.E. Logan, 2010). But considering the facts that ferricyanide is a toxic compound, is not easily disposable and is usually used when research and investigation needs to be considered for the anode chamber only (B. Tartakovsky and S.R. Guiot, 2006). Hence, oxygen being the only one left, even tho other electron acceptors may be used, but oxygen provides a more practical use and is in abundance (B.E. Logan, 2009). And almost every cell which has large scale application will use oxygen. Therefore, for this particular project they will be using an air-cathode chamber MFC system.

There are a number of different experimental designs which can be implemented in an MFC system. The simplest MFC system is the sediment MFC, which operated by an anode which is place deep in the soil where there is minimum amount of oxygen and it will be consumed by aerobes or facultative anaerobes in the sediment (He et al, 2007). There are a variety of different experimental designs for MFC systems, but many of which have a small impact outside the lab and cannot be used on a larger scale outside the lab setting. But they can work better to understand the limitations and optimizations for experiments which may be conducted (Dumas et al, 2007). Usually the most practical design of air-cathode chamber design is to suspend the cathode in a rich oxygenated environment exposed to air above water while the anode is in the water (He et al, 2007). MFC systems which are designed in a manner of an air-cathode are inexpensive and saves costs, they do not require any catalysts, and lastly a selective material for a membrane as an ion exchange membrane is not needed, as most of the microbes will pass through the sediment where the anode is placed with minimum oxygen, but keeping in mind that sediment MFCs provide little power production (Donovan et al, 2008). Even though sediment MFC provides little power production, and cannot be used in wastewater treatment does not mean they are not useful.

Sediment MFCs can be used in niche applications which require small amount of power such as temperature probes, and small marine probes which do not consume a huge amount of energy. The simplest experiment is of the MFC system can be studied and/or researched on a lab scale whereby soil is collected in a jar and the anode being placed in the jar (Zhang et al, 2010). Furthermore, an addition of an activated carbon may be added in the air-cathode chamber to enhance the power production in the system. In this study pulverized activated carbon was used to enhance the power production.

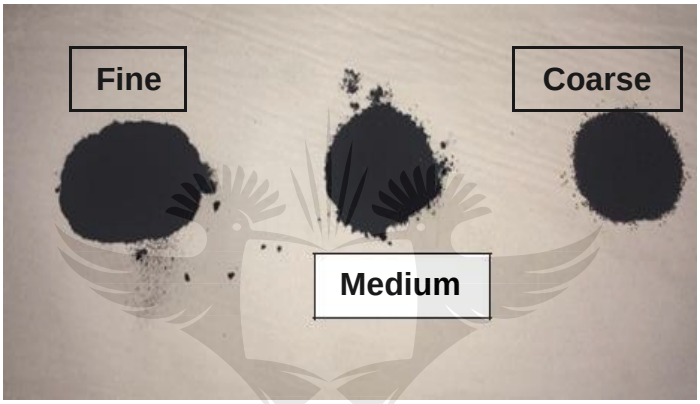


Fig. 2.3.1. *– Pulverized activated carbon sizes.*

There are more complex MFC system designs which involve a 2 chambered MFC, which includes an anode and a cathode chamber which are rectangular in shape (Zhang et al, 2010). The cathode chamber is suspended in an aquas solution usually in water and the two chambers are pressed together and between them there is an ion exchange membrane to allow and assist in proton transfer from the anode to the cathode. And these two chambers are held together by external bolts, which allows for adjustments to the size of the MFC design system (Nevin et al, 2008). This type of design provides a larger area of ionic transfer between the anode and cathode chamber. The downfall of the design is the difficulty involved in assembling and tightening the bolts which can be time consuming. Below are the views of a single chambered MFC with a PEM and cathode.

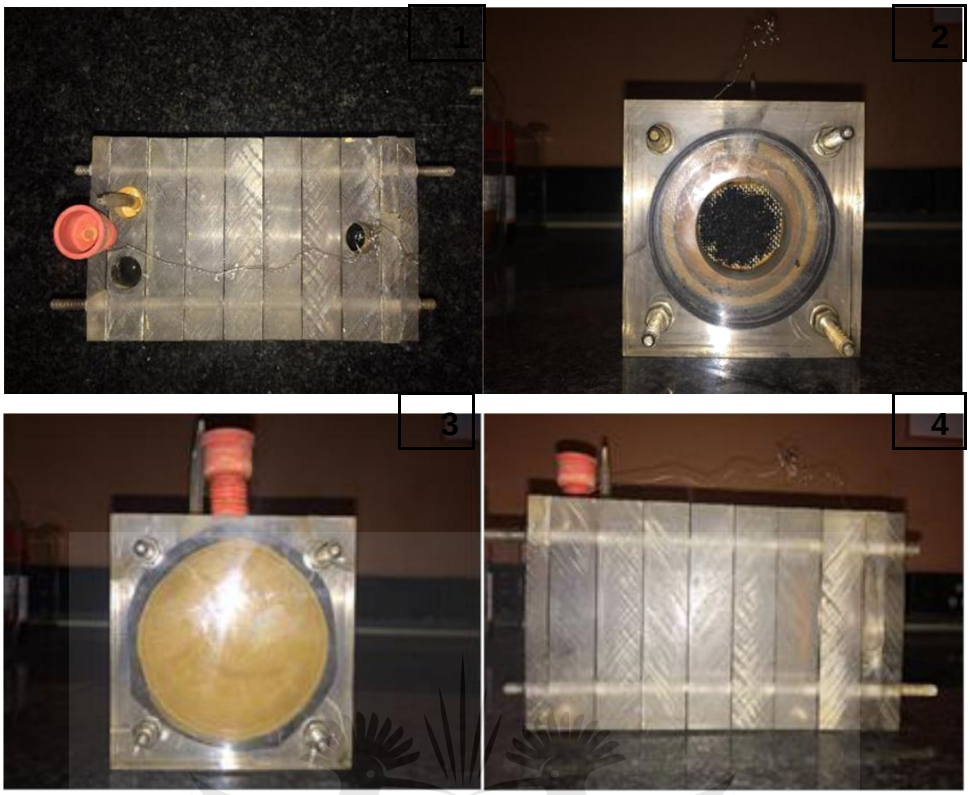


Fig. 2.3.2 *– A Single-chambered MFC with a PEM and cathode. 1) Top view. 2) Front view. 3) Back view. 4) Side view.*

Usually the cathode chamber is exposed to the air in order to use the ambient air rather than using pure oxygen. The above system design has an aqueous anode which has a feedstock of synthetic wastewater within its capacity volume. The mentioned above MFC system design with an air cathode is the most used and most practical design, this is because its cost effective and lower operating costs for the overall system. Therefore, referring back to the previous section it can be seen that the design system of an effective MFC is that which s rectangular in shape. Needless to say, that there have been a lot more designs and orientations which have been used in the study of MFC design systems (Rabaey et al, 2005). Shapes like the H-type fuel cells and tubular up flow air-cathode MFCs have been studied as well. The typical brief operation of a tubular up flow works in a sense of the tube have whole on the anode and the cathode wrapped around it (You et al, 2007).

This type of design allows for a larger area where a transfer of ions can take place between the anode and cathode (Kim et al, 2010). Detailed information will be covered in this section. The above mentioned MFC system design may provide an advantage of a selective material ion exchange membrane to be removed (H. Liu and B.E. Logan, 2004). This will only depend on the cathode electrode that is being used in the system which will accommodate the removal of the ion exchange membrane (You et al, 2007). The removal of an ion exchange membrane provides cost savings because the PEM is one of the most expensive materials which are used in the design (H. Liu and B.E. Logan, 2004). An MFC system which has a PEM will have an increase in internal resistance due to the disability for ions to be mobile more frequently to pass through the membrane. Hence the removal of an ion exchange membrane leads to an increase performance in power production for the whole system (B.E. Logan, 2009). Even though the removal of a PEM increases the performance of the cell, this will lead to certain complications in the system (Oh et al, 2009). The design of an MFC without a PEM will allow an increased amount of oxygen to diffuse within the anode chamber and as discussed in the previous section this will cause inefficiency in the system and maybe toxic to the feedstock (culture medium) in the anode chamber (Z. Liu and H. Li, 2007).

Fig. 2.3.3 *– Top view dimensions of anode and air-cathode (Ratio size).*

2.3.1 Single Chamber Microbial fuel cells

A typical one-compartment MFC eliminates the need for the cathodic chamber by exposing the cathode directly to the air. The one-compartment MFC consists of an anode in a rectangular anode chamber coupled with air-cathode. Protons are transferred from the anolyte (anode chamber) solution to the porous air –cathode. The single-chamber is the easiest to scale up as it uses air directly as the oxygen source and also due to less material is required thus less overall cost. The cube is usually made of perspex plastic.

2.3.2 Double chamber Microbial fuel cells

Double chamber configuration is the most widely used consisting of two compartments with the anode and cathode separated by the proton exchange membrane. The anode chamber is kept oxygen free for anaerobic breakdown process to occur. Although the H-type or dual-chambered microbial fuel cells is the most common in laboratory use, it is the most challenging to scale up due to the impractical configuration. This set up can accommodate various electrode shapes, as it has dedicated chambers for the anode and cathode. (Du et al, 2007). It can also use other catholyte besides air, which is any source of oxygen. (Campo, 2013).

2.3.3 Tubular chamber Microbial fuel cells

The single-chambered, tubular, continuous microbial fuel cell uses granular graphite matrix as the anode which generates high power outputs. This type of MFC has proven to be most effective in continuous flow operation (Scott et al, 2007). This set up does not require a strictly controlled anaerobic environment and adapted the form of a helix which allows the fuel to flow through at a certain flow rate. (Scott et al, 2007). This MFC configuration is most applicable in commercial use as it yields high power densities with minimum cost in terms of the materials used. The coiled helix tubular MFC concept might be the next step to realising practical applications.

2.4 Microbial fuel cell components

The microbial fuel cell consists of simple yet vital components for its function which are:

Electrodes: Both in the anode and cathode chambers

Proton Exchange Membrane: Widely used Nafion as the least resistive membrane

Substrate: Any organic matter used as source of energy for microorganism's i.e. domestic wastewater

Bacteria: Exoelctrogens, most suited for MFC applications

Table 2.1: *Basic Components of microbial fuel cells*

Items	Materials	Remarks
Anode	Graphite, graphite felt, carbon paper, carbon-cloth, Pt, Pt black, reticulated vitreous carbon (RVC)	Compulsory
Cathode	Graphite, graphite felt, carbon paper, carbon-cloth, Pt, Pt black, RVC	Compulsory
Anodic Chamber	Glass, Plexiglass	Compulsory
Cathodic chamber	Glass, Plexiglass	Non-compulsory
Proton Exchange Membrane (PEM)	Nafion, Salt bridge	Compulsory

2.4.1 Electrodes

The efficiency of an MFC is dependent on a number of factors and one is the material of the electrodes. There have been many MFC designs and configuration that have been tested and developed in recent years to improve the performance and efficiency of MFCs. However, the challenge to find the balance between performance and material cost remains difficult. (Wei et al, 2011). The electrodes have a certain resistance hence the most effective ones are the least resistive. The anodic resistance contributes to the overall cell resistance in MFC operation. (Liu, 2013). The material characteristics which are critical for an effective electron transfer are high conductivity and mechanical strength. There is no requirement for bacterium adhesion. The scalability and cost-effectiveness are also taken into consideration. Type of electrodes;

Plane structure: Carbon paper, graphite sheets or plates

Packed structure: Granular graphite, and or activated carbon

Brush structure: Carbon felt, reticulated vitrified, carbon brush

Stainless steel mesh

Anode electrode

Anode electrodes are usually made of a planar conductive material which will allow electron donation to the other electrode in a different chamber (D.R. Bond and D.R. Lovley, 2003). Microbes in the anode should be able to respire on a stainless-steel plate electrode, which is used in this project on the cathode chamber (Richter et al, 2008). There are a number of materials which can be used as anode electrodes, which will be shared in this section (Dumas et al, 2008). Higher power densities may be generated by using electrodes in the anode chamber which are porous in size and are rough on the surface (Liu et al, 2010). The specification on the electrode will provide the formation of a biofilm for the culture medium fed into the anode (Qiao et al, 2010).

Microbes are sensitive to the type of material used for an electrode; any type of conductive material is ideal to be used but should not be toxic to the electrically active species in the anode chamber volume (Zhou et al, 2011).

The most common MFC materials being used in current studies are that which are more porous and usually made of conductive carbon. In this project study, a carbon coated PTFE is used as an anode electrode (Zhou et al, 2011). There are certain materials which can be used such as carbon paper, carbon felt, carbon cloth, and carbon tissue fibres. These electrodes provide the system with high amounts of conductivity because of their surface area (Liu et al, 2011). Beside the use of a large surface area for the carbon electrodes, they in addition are useful when it comes to corrosion resistance. This proves as an advantage to other metal-based electrodes such as copper electrodes which are significantly toxic to the feedstock (culture medium) in the anode chamber and will act as a parasite to the electrically active species (Srikanth et al, 2011). The biggest disadvantage of using carbon-based electrodes is that they have a difficulty in allowing substrate to diffuse into the carbon material electrode while in return the protons which need to be donated to the cathode chamber find it difficult to diffuse out of the electrode (Liu et al, 2010). This contradiction of mobility of ion transfer will in turn increase the internal resistance in the overall cell and may lead to acidification in the system due to the contradiction of mobility on the carbon-based electrode (Aelterman et al, 2008). Therefore, there is a need to report any projected surface areas, for the anode electrode in order to find the most optimum surface area which will find a balance between the contradictions. Two types of designs have been implemented in MFC systems:

1. Surface area enhancement for microbes to attach to the electrode has been optimized by the use of rod which had been sprayed with granular graphite (You et al, 2008). As mentioned earlier that graphite is a good conductive material.
2. Surface area enhancement was also optimized by the use of bottle brush electrode which provided a large surface area for microbes to attach for adhesion (Logan et al, 2007).

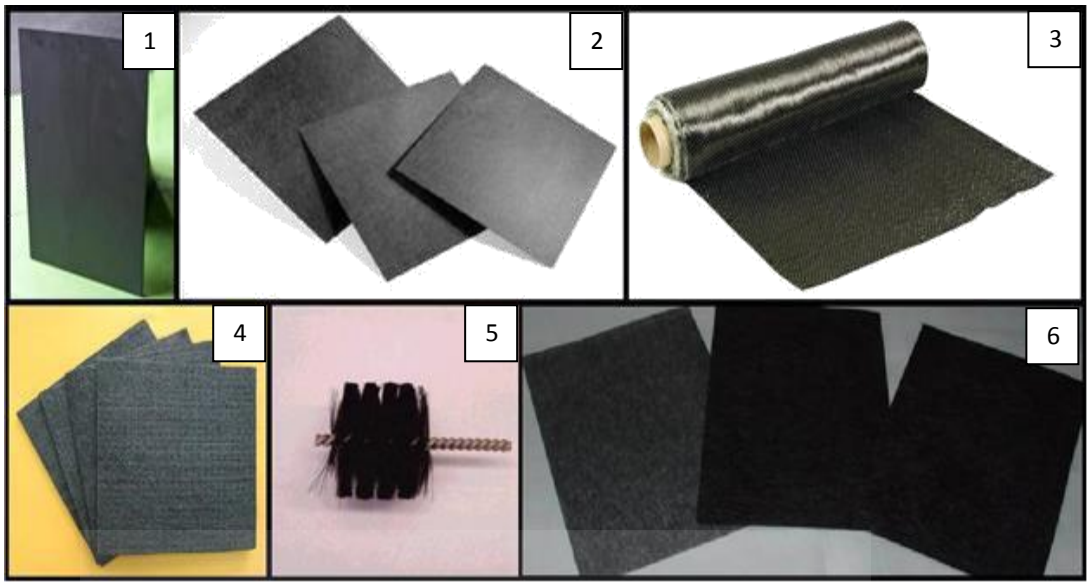


Fig. 2.4.1.1 *– Some possible materials for MFC anodes. 1) Graphite plate. 2) Carbon paper. 3) Carbon cloth. 4) Carbon felt. 5) Graphite fibre "bottle brush". 6) Carbon fibre tissue*.

Cathode electrode

Taking a look at hydrogen fuel cells, these types of fuel cell systems have both their electrodes (anode and cathode) in a single membrane assembly. Usually the cathode electrode in the design system is an air-cathode, and this makes the hydrogen fuel cell available commercially (V. Mehta and J.S. Cooper, 2003). These types of fuel cell system design have been closely packed to each other. This is done by means of hot pressing the anode electrode typically it will be a carbon cloth coated with a certain percentage of PTFE, pressed together with the selective proton exchange membrane in addition to the cathode electrode (V. Mehta and J.S. Cooper, 2003). More layers need to be added to both the electrodes in order for the system to take advantage of the diffusion layers of hydrogen and oxygen to the electrode surface areas (Cheng et al, 2006). And the main reason why the carbon cloth is coated with a PTFE is for wet proofing which assists in water elimination in the cathode chamber. In an MFC system, considering the half-cell reaction. The oxygen reaction in the system is quite slow and this needs to be enhances or pushed faster by the aid of a catalyst.

The most common types of catalysts which are used is platinum, but platinum has its own disadvantages because it is expensive to buy (Kim et al, 2009). And the expenses may reduce the revenue which needs to be capitalized in order to reduce costs. Due to the amount of money or costs needed to purchase this catalytic metal, researchers need to make sure that the surface area of the catalyst is exposed to its maximum in order to capitalize on the surface area exposure (Velasquez-Orta et al, 2010). There are certain techniques which can be implemented to allow for maximum exposure of the catalyst. One of these frequently used techniques is spray platinum particles on the desired electrode. This will allow more surface area to be covered with minimum amount of the catalyst spent, typically an amount if 0.5mg/cm2 is used in most MFC literature, but yet again this will highly depend on the mass of platinum its self (Kim et al, 2005).

As discussed in this section about hot pressing the two electrodes to the PEM. Hot pressing results in an increase in oxygen concentration in the anode this is because the anode and ion transfer membrane are placed together which results in an electrically active biofilm in the system. Usually not hot-pressing the anode electrode to the PEM can be used and optimized for a few other reasons.

1. Anodes have a disadvantage of not being able to be pressed to electrodes, due to the type of material which they are made of.
2. Remembering when an electrode is hot pressed only one surface will be exposed in the system, so basically this means that the reaction surface area is will only be 50% operational. And this reduces the reaction of bacteria adhesion and transfer of these substrates will be restricted even further (Liu et al, 2005).
3. During this study, it is known that an air-cathode MFC system oxygen will be diffused from the cathode chamber through the ion transfer membrane. So, there are limitations as to hot-pressing being an advantage to optimum power production (M.M. Ghangrekar and V.B. Shinde, 2007).

The removal of an ion exchange membrane provides certain advantages such as allowing anodic membranes to act and allow electrolytic activity to take place between the two placed anode and cathode electrodes (You et al, 2007). These electrolytic activities have been proven by researchers during numerous of experiments (H. Liu and B.E. Logan, 2004). As mentioned previously, wet proofing of a PTFE will result in a prevention of the cell not to dry-out (Zhou et al, 2011). As the ion transfer membrane is quite permeable to water or any other aqueous solution depending on the viscosity when eliminated in the system (Cheng et al, 2006). The whole system design will lead to a stand-alone cathode (Liu et al, 2005). Techniques such as wet proofing are advantageous in fuel cells to allow water to drip off the cathode in the cell. This will result in a removal of the limitation to oxygen diffusion.

2.4.2 Proton exchange membrane

The proton exchange membrane is a core component that greatly influences electrochemical performance in MFCs. The PEM has a structure which enables only hydrogen ions or protons to pass through. Hydrogen with proton exchange membrane is currently considered as a potential next generation alternative energy technology because of the high energy density and high abundance of hydrogen in nature. (Ngo et al, 2013). The most widely used polyelectrolyte for proton exchange membrane is the Nafion which increases the three-dimensional zone of catalytic activity.

2.5 Setup and operating conditions

MFC systems are sensitive to the type of design they implement, there a number of situations at which an MFC can be setup and operated. The way in which they are setup and operated have a significant effect on the efficiency of the system and effective power production. As previously mentioned one of the most critical components in an MFC system design is the presence of an ion exchange transfer membrane. When an MFC system does not have a PEM, this provides an advantage of reducing the

internal resistance in the cell, but at the same time has a downfall of increasing oxygen diffusion in the system compared to a system which has an ion exchange membrane (Liu and Logan, 2004). The maximum power density in the membrane-less cell increased to 494 mW/m2 compared with 262 mW/m2 in a cell with the PEM (Liu and B.E. Logan, 2004).

An introduction of a PEM in an air-cathode chamber system will enable the diffusion of additional cations to pass through the membrane and accumulate on the cathode chamber. This electron movement in the system is caused by other cations which are in abundance to pass through the PEM and balance the charge transfer (Rozendal et al, 2006). The inability of the PEM not allowing a sufficient amount of protons to pass through the membrane will result in a rise of pH levels, because the cathode chamber requires protons to have an effective reaction in the half-cell reaction. The process of rising pH will affect the anode reaction by slowing down the forward reaction of the half-cell reaction. The resultant of this will be the formation of precipitates on the cathode surface (Rozendal et al, 2006). Precipitates which are formed on the cathode electrode are not required and should be removed, but the biggest problem with the removal of these precipitates is the complexity techniques which are required. Typically, precipitates are removed by using deionized water to rinse of the outer surface of the cathode electrode.

Fig. 2.5.1 *– Deionized water for precipitation removal.*

One of the most important setup and operating conditions is the distance between the anode and cathode chamber in the system. An MFC system with a PEM will indeed have internal resistance which is the sum of the resistance of the culture medium (electrolytic) and obviously the PEM itself which is added to the cell. But for an MFC system without an ion exchange membrane, the overall internal resistance is due to the distance between the anode and cathode chamber. It should not be forgotten that there will always be resistance in the system this addition of resistance is caused by protons moving from the anode chamber to the cathode chamber through a biofilm or a porous electrode. Although this does not stop the operation of an MFC system, certain considerations need to be taken such as; minimizing the overall distance between electrodes, which will ideally result in an increasing trend of power production with the reduced spacing distance between the electrodes in both chambers (Liu et al, 2005).

The feedstock (culture medium) should have a high ionic strength because the ionic strength does affect the conductivity of the electrolyte in the system. Usually in fuel cells a high ionic strength is generally achieved by an addition of acidity or basic solution. But when concentrating our investigation to MFC systems this addition will kill the electrically active

species and obviously reduce power production. But another way which can be used in increasing the ionic strength is through an addition of salts (NaCl) concentrations (Liu et al, 2005).

2.6 Synthetic wastewater

The study in this project was using synthetic wastewater as the feedstock. It has been noticed domestic wastewater has around 100mg/l of DOC concentration, and this can be achieved by using synthetic wastewater as the feedstock. Preparation of the synthetic wastewater involves the following (This preparation was aided with the use of OECD/OCDE guideline for testing of chemicals);

Dissolve in each litre of tap water: peptone, 160mg; meat extract, 110mg; urea, 30mg; anhydrous dipotassium hydrogen phosphate (K_2HPO_4), 28 mg; sodium chloride (NaCl), 7 mg; calcium chloride dehydrate ($CaCl_2.2H_2O$), 4 mg; magnesium sulphate heptahydrate ($Mg_2SO_4.7H_2O$), 2 mg. This OECD synthetic wastewater is an example and gives a mean DOC concentration in the influent of about 100 mg/l.

Alternatively, use other compositions, with about the same DOC concentration, which are closer to real sewage. If a less concentrated influent is required, dilute they synthetic wastewater, for example 1:1, with tap water to obtain a concentration of about 50 mg/l. Such a weaker influent will allow better growth of nitrifying organisms and this modification should be used if the simulation of nitrifying wastewater plants is to be investigated. This synthetic wastewater may be made up of distilled water in a concentrated form and stored at about $1^{o}C$ for up to one week. When needed, dilute with tap water. (This medium is unsatisfactory e.g. nitrogen concentration is very high, relatively low carbon content, but nothing better has been suggested, except to add more phosphate as buffer and extra peptone. (OECD guidelines for the testing of chemicals, 2001).

Fig. 2.6.1 *– 10 L synthetic wastewater.*

2.7 Activated carbon

Typically, the MFCs performance can be enhanced through an addition of a catalyst to favour the forward reaction taking place in the system. In the recent years platinum has been used as a catalyst to enhance power production for MFC systems. But this metal (platinum), has some major disadvantages because it is expensive and it is a rare metal. And hinders the capabilities of the MFC technology to scale-up due to their cost implication which comes with it. Researchers has looked into finding other source which may be used in substitution of platinum. In our investigation activated carbon granules have been used as a catalyst.

Fig. 2.7.1 – Activated carbon.

2.8 Power and Efficiency

Power and efficiency are one of the parameters which researcher look into. Most MFC system parameters provide difficulty in comparison. This difficulty is caused by factors attained to the way the experiments are performed in reporting power density which is only stationary to anodic surface area, cathodic area, or membrane area. So, this makes it quite difficult to compare the power densities of any MFC system. The problem will be keeping one component stationary is that if the very same anode, cathode, or membrane is placed in a smaller volume then the one previously investigated, they may find that it will obtain the same current densities with a significant increase in power production. Currently the highest power density recorded via volume in the anode as a normalized component was between 2 – 2.15kW/m3 (Nevin et al, 2008).

During the study of this project, synthetic wastewater was used and activated carbon pressed to a stainless-steel mesh to an air-cathode in a two chamber MFC rectangular stack with oxygen been the main electron acceptor and CSI 7000S PEM. The anode was roughly 1/6 the size of the cathode chamber.

The removal of an ion exchange membrane will result in lowering the coulombic efficiency of the overall system. The reason for this reduction is due to the fact that oxygen will be reduced directly in the anode chamber hence slowing down the activity kinetics of the system and disturbing any

further metabolism of electrically active species in the feedstock. An MFC system with an air-cathode system resulted in a coulombic efficiency in the range of 40 – 55% with the presence of a PEM, but only 9 – 12% for an MFC system without a PEM (Liu and Logan, 2004).

2.9 Application of microbial fuel cell

Electricity generation is needed to purify water and use water (hydro-generation) to produce energy. A significant fraction of the electricity generated is used to power the water infrastructure. The hope in the future is that wastewater treatment plants which consume electricity to power plants generating electricity. Electricity produced by MFCs may never be a cost-effective source of energy in its own right. Rather their contribution will be one of reducing the energy used in wastewater treatment. (Gaviria, 2011). Wastewater treatment systems consists of a series of unit processes each having specific functions which contributes to purifying the influent as it passes through the different stages. One of the stages involves aerobic biological processes which require both oxygen and food in order for the bacteria to live. The bacteria consume biodegradable soluble organic contaminants. A power management system (PMS) is proposed as a method of increasing the power output by use of transformers, capacitors and converters. (Zhang et al, 2009) conducted tests to evaluate the feasibility of charge pump-capacitor-converter and capacitor-transformer-converter PMSs which yielded promising results.

MFCs have shown to successfully treat wastewater which include domestic, animal, brewery and food processing wastewaters and generate current in the process. (Ahn & Logan, 2013). Using domestic wastewater as fuel source, an experiment conducted by (Rodrigo et al) reported that using anaerobic pre-treatment of activated sludge; electricity generation can be obtained in a short time period (8-10days). The oxygen used is very small (only 0.25% of the influent chemical oxygen demand (COD)) for electricity-generation processes. The max power densities is around 25mW/m2 with a voltage of 0.23V using domestic wastewater. (Rodrigo et al, 2007).

CHAPTER 3

EXPERIMENTAL METHODOLOGY

3.1 Assembling of MFC single chamber

Assembling of an MFC system is to ideally assemble all the cells in a stack formation and identical to each other. Take note that an assembly of an MFC should be tightened and avoid leakage in the system. The first step is to ensure that the compartments are clean and sterile from any contamination. Once cleaning has been achieved they will have to place the PEM at the back end of the anode chamber together with the anode electrode which they have used a carbon cloth coated with PTFE. After this has been done, the electrode will be attached to a titanium wire. Secondly, they will then stack the rest of the cell identical to each other and once they have stacked the cell to about 5cm they will then place a PEM in between the cells. The remaining few steps is to places the stainless-steel mesh which is pressed with activated carbon at the end of the opening of the cell. Diagrams are shown below, on the steps of component assembling. The stainless-steel mesh serves as a spacer that will prevent a short circuit in the system. The attached cathode electrode is placed at the end of the cell and on top of the gasket, which is than connected to a titanium wire current collector. The titanium wire is then punched through the mesh and tightened to allow for more surface area to be utilized. And lastly the front cover with an opening is placed to complete the MFC system.

The whole cell cover of the MFC is then bolted using 4 bolts, 8 nuts and 8 washers to distribute the pressure. Each nut is then tightened and a washer should be placed first before tightening the nut as this will allow a good grip due to the friction force between the washer and nut. Be precise when tightening the cell as an under tightening will result in a leakage of the MFC

system and the consequences of leakage have been previously discussed, and further this will cause the components to move around within the system. But, overtightening will also cause the whole cell to expand outwards. The main reason for a precise and standard tightness is that the forces within the anode chamber may cause the carbon cloth to rip and this will also have an effect on the distance between the electrodes, so hence a standard tightness is required to keep a uniform MFC system distribution which is normalized throughout.

Table 3.1: *Assembling of MFC single chamber*

	Assembling of Single chamber	**Responsible Person**
OBJECTIVE	To prepare a chamber with anode and cathode compartments for the synthetic wastewater.	(The author).
SAFETY	Ensure that they have the correct Personal Protective Equipment, (safety gloves, safety goggles, lab coat, long pants and closed shoes).	
	PROCEDURE FOR ASSEMBLING	
1. Prepare a solution of distilled water	This procedure will require the use of clean distilled water about 2L at room temperature. Firstly, ensure that the distilled water has not been contaminated.	(The author).
2. Cleaning of single chamber.	Take the ten pieces of the single chamber and wash/clean them with soap. A specific procedure should be followed when cleaning the single chamber before use. Firstly, ensure that they apply soap on each individual piece and wash it with warm tap water. Follow this procedure for all components (the ten pieces). After completion of the cleaning, rinse all the single chamber compartments with the prepared distilled water, this is to ensure that they sterilize all components.	(The author).
3. Assembling of anode and	Firstly, ensure that they have a stainless-steel mesh, proton exchange membrane (PEM) CSI 7000S and a carbon cloth (PTFE) of a specific coating either 0%, 30%, 40% and 50%.	(The author).

cathode compartment.	Key note: The surface areas of the membrane, carbon cloth and stainless-steel mesh should be 36cm^2. The anode compartment will consist of a carbon cloth which is attached to a titanium wire in an anaerobic state. The cathode will have stainless steel mesh which is attached to a titanium wire in an aerobic state and a PEM. The membrane in the cathode should be 11cm away from the anode chamber. Measurements are taken from the carbon cloth in the anode to the membrane in the cathode chamber.	

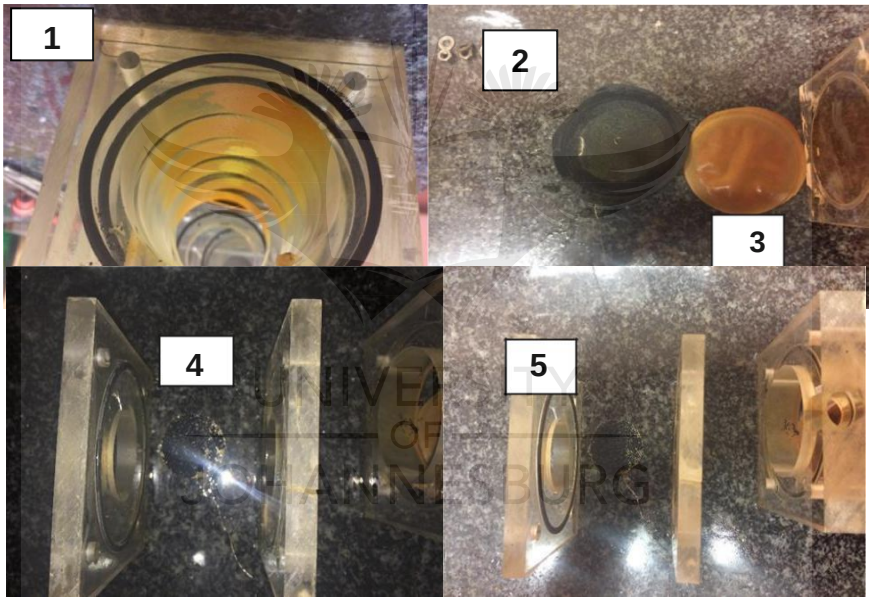


Fig. 3.1.1– *Order of components for MFC assembly. 1) Anode chamber; 2) Coated carbon cloth, connected to titanium wire current collector; 3) Proton exchange membrane separator; 4) Activated carbon pressed to stainless steel mesh, with titanium wire current collector; 5) Opening from anode chamber to the open air-cathode chamber.*

3.2 Preparation of synthetic wastewater

Table 3.2: *Wastewater preparation*

	Wastewater preparation	**Responsible Person**
OBJECTIVE	To prepare a sample of synthetic wastewater for microbial fuel cell.	(The author).
SAFETY	Ensure that they have the correct Personal Protective Equipment, (safety gloves, safety goggles, lab coat, long pants and closed shoes).	
	PROCEDURE FOR COLLECTION	
1. Collection of wastewater	The wastewater was prepared in the lab. Take about 10L of tap water and pour it in a jar. Measure: 1.6g of peptone, 1.1g meat extract, 0.3g urea, 0.28g sodium chloride, 0.04g calcium chloride dehydrate. Pour the mixture into the 10L of tap water jar After preparation of the synthetic wastewater, ensure that the solution is refrigerated in a cool/cold environment. This is to ensure that the microbes will not die.	(The author).

Fig. 3.2.1*– Chemicals used for synthetic wastewater. 1) Peptone. 2) Sodium Chloride. 3) Calcium chloride dehydrate. 4) Urea. 5) Meat extract.*

3.3 Sampling (Taking readings)

3.3.1 OCV, Voltage and Amps

Table 3.3: *OCV, Voltage & Amps*

	Taking readings **OCV, Voltage & Amps**	**Responsible Person**
OBJECTIVE	To get the overall voltage running through the circuit where both terminals are connected to an external load/resistor.	(The author).
SAFETY	Ensure that they have the correct Personal Protective Equipment, (safety gloves, safety goggles, lab coat, long pants and closed shoes).	
	PROCEDURE FOR OCV READINGS (Daily)	
1. Connect a multi-meter to the fuel cell	This procedure will require the use of a multi-meter. Firstly, connect the red (negative terminal) cable to the cathode and the black (positive terminal) cable to the anode compartment. Secondly adjust the multi-meter device to take voltage on a normal scale (10^1). Lastly as the red and black cables are connected to the titanium wire in the anode and cathode allow the multi-meter to take readings. Key note: Values on the multi-meter will increase at a steady pace, therefore only take the last reading where the values have stabilized. The value taken will be the OCV (open current voltage).	(The author).
	PROCEDURE FOR VOLTAGE & AMPS READINGS (Daily)	
2. Connecting an external load	Before they take voltage readings which are connected to an external load they need to adjust the external load. Connect an external load to the anode and cathode compartment. Firstly, apply a 2400 ohms resistantance and decrease in 200 ohms intervals until 0 ohms (i.e 2400, 2200, 2000 etc). For each external load they will apply the load for 5minutes and once the time has elapsed they then connect a multi-meter to take the voltage reading. After taking our voltage reading they can then calculate our current by using ohms law for that specific external load. Repeat point 2, 3 &4 until they reach 0 ohms.	(The author).

3.3.2 COD levels

MFC systems main goal is to treat wastewater while ideally taking advantage of power generation. COD levels are taken before the experiments can take place; these are usually around 100 mg/l for an influent taken from raw domestic wastewater. As discussed previously that synthetic wastewater was used which had a DOC concentration level of around 100 mg/l but may be further diluted to 50 mg/l depending on the operating conditions required. COD levels indicate that the system is indeed treating the wastewater; this will be noticed by a reduction in the COD concentration levels. Standard hatch samples where used to measure the readings for the COD levels for every experiment. Usually these readings are taken before the experiment and preferably mid-way through the experiment and at the end of the experiment. The procedure undertaken for these measurements are described below.

Fig. 3.3.2.1 *– Before and after COD testing bottle for MFCs.*

Table 3.4: *COD levels*

	Taking COD levels	**Responsible Person**
OBJECTIVE	To get the Chemical oxygen demand, this is to indirectly measure the amount of organic material in the water, also ensuring water quality.	(The author).
SAFETY	Ensure that they have the correct Personal Protective Equipment, (safety gloves, safety goggles, lab coat, long pants and closed shoes).	
	PROCEDURE FOR COD READINGS	
1. Take standard hatch samples to measure the COD levels	This procedure will require the use of a hatch machine, which will give us the COD levels in mg/L. Firstly, take three (3) standard hatch samples. (One for before treatment has begun and the other is after the experiment has ended). This will give us the difference in COD levels of before and after Secondly before starting with the experiment pour only 2mL of the synthetic wastewater and after the experiment pour 2mL in the other hatch standard cylinder. Thirdly, put all three samples (Standard hatch sample, before, and after the experiment solutions) in the hatch oven at 150^{o}C for 120minutes. Once complete allow the samples to cool down. Lastly, take the three samples into the hatch machine for analysis and take the COD levels for all three samples. Key note: The samples should be cooled before being analysed in the hatch machine. And COD levels are to be taken before and after the experiment.	(The author).

3.3.3 Temperature and pH

Temperature control in an MFC system is highly important as the operation and feedstock relies on the temperature at which the kinetics of the electrically active species takes place. From previous literature it has been noticed that the most optimum temperature at which the system should operate at is 35 ^{O}C, a temperature controller was used and set to the required temperature and placed in the ecobath to complete the system. The anode chamber was submerged in 8L of tap water within the ecobath together with the temp control to keep both chambers in system at the same temperature. Keeping the system temperature is very important as this give high probability of the whole cell to operate efficiently without any lose in power production.

pH readings are of the utmost importance, and as discussed previously that the pH should be kept at 7 (neutral) as possible as acidity and/or too much basicity will slow down the anode organism metabolism. But to enhance the efficient without interrupting with the system NaCl may be added to increase ionic strength of the system without increasing too much acidity and basicity within the cell.

Fig. 3.3.3.1 *– Temperature controller maintaining MFCs condition.*

Table 3.5: *Temperature and pH*

	Temperature and pH readings	**Responsible Person**
OBJECTIVE	To maintain temperature and pH levels constant throughout the experiment.	(The author).
SAFETY	Ensure that they have the correct Personal Protective Equipment, (safety gloves, safety goggles, lab coat, long pants and closed shoes).	
	PROCEDURE FOR MAINTAINING TEMTERATURE & pH	
1. Set the temperature on the ecobath	This procedure will require the use of a heating element which is placed in the ecobath to maintain a constant temperature of 35^0C.	(The author).
2. pH readings.	Both pH levels in the anode and cathode are to be kept neutral (pH of 7). The cathode chamber is to be filled with 8L of tap water at a pH of 7 and the anode is to be at a pH of 7, any change in pH levels will be stabilized using a buffer solution. Take the pH readings using a pH meter. Readings are to be taken daily.	(The author).

3.3.4 MFC Monitoring

MFC system was monitored using a voltmeter and external resistance between the anode and cathode chamber, this allowed the monitoring of the cell potential. Typically, this was accomplished by setting the voltmeter reading to zero and not applying an external resistance to measure the open current voltage (OCV). To accomplish an accurate measurement, the anode chamber should be the reference electrode within the system. Both the connection of the anode and cathode for the measurement of cell potential is referenced to the anode chamber. Constant external resistance of 200 ohms from 2400 ohms was taken to draw the required curves. Ohms law (V = IR) was used to determine the current and power production of the system.

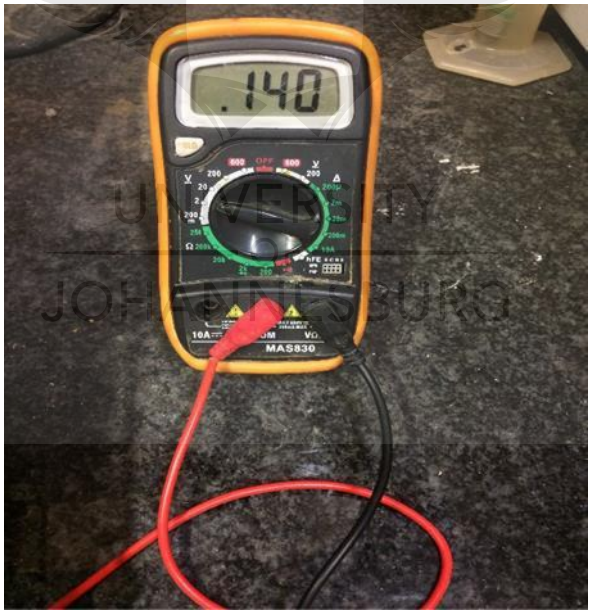


Fig. 3.3.4.1 *– Voltmeter for voltage reading.*

3.4 Laboratory equipment

Certain laboratory equipment were used in the experimental work:

3.4.1 Multimeter (DT9205A-Aaron)

A DT9205A-Aaron multi-meter display device was used to measure (take readings) of the voltage, current and external resistance.

3.4.2 DR 3900 Spectrometer (Hatch Loveland machine)

DR 3900 spectrometer machine was used to measure the concentration and COD levels before and after each experiment.

3.4.3 pH meter

A pH which is an electronic device that was used to measure the pH (acidity or alkalinity) of a liquid, to measure the pH of a solution, the probe is dipped into the solution.

3.5 MFC setup-inoculation

The MFC system is initially sterilized and clean first as preparation for the feedstock to avoid any contamination in the system. There are certain scenarios where by inoculation may fail. It has been noticed that large volumes of cathodes should be avoided as this may cause increased internal pressure in the system due to the amount of pressure that will be required to assembly the system. This internal pressure will result in a leakage of the cathode because it could have burst during assembling. In our experiments and observation, it did not experience any cathode leakage and it is safe to state that these leakages were quite rare in our investigations. If the cathode had to crack or burst the whole project will come to a halt and the replacement of this cathode will be costly.

Another issue is evaporating heating taking place in the cathode chamber. From our previous section it is noted that the presence of electron acceptors such as oxygen may cause precipitation and may be removed using deionized water. But to avoid evaporative heating they need to constantly add roughly around 500mL of tap water in the cathode to keep the anode submerged in water to allow efficient organism metabolism.

Table 3.6 *– MFC constant/specific data of experiments.*

Chambers:	**Anode and cathode**
Length	Anode: 25cm*13cm Cathode: 30cm*40cm
Membrane:	**CSI 7000S**
Thickness	177.8 um = 0.1778 mm
Electrodes:	**Anode and cathode**
Thickness	0.1 cm = 1 mm Area: 36 cm^2
Temperature:	35 ^{o}C
pH:	7 - 7.5

Fully assembled MFCs which have been filled with feedstock (synthetic wastewater) are then placed in the ecobath with tap water at a constant temperature. The anode chamber has a gas inlet valve, and since no oxygen is needed in the anode chamber, a cylinder tube filled with water is connected to a pipe which will feed into the anode chamber to avoid any access to oxygen within the system. During this process a voltmeter is connected without any resistance being applied to the system, measuring the OCV to ensure that there is a potential difference in the cell. The reading obtained from the voltmeter will let us know that the cell is operating well and efficiently at the beginning of the process. Usually 24hours after operating the system, current readings need to be taken.

They are taken from highest to lowest, but keeping in mind that the OCV should be taken first before any external resistance is to be applied on the system. Once that is done, an external resistance of 2400 ohm will be applied to the system for about 5min to allow resistivity to settle, after the 5min has elapsed, external resistance is removed and volt readings are taken to calculate the current at that point in time using Ohms law. This step will happen continuously while decreasing the external resistance by intervals of 200 ohms until 0 ohms is reached.

Fig. 3.5.1 *– Final MFC system, with connections to voltmeter.*

3.6 MFC operation

MFC operation begins as mentioned previously when the anode is submerged in the ecobath which acts as the cathode, at the required temperature. And double checking whether there is a potential difference in the cell by taking an OCV reading for confirmation.

Initially, immediately after the feedstock has been fed into the anode chamber, a 2mL sample is taken at the beginning of the experiment to get the initial COD levels. Certain steps need to be followed as explained previously when taking COD levels. These readings will be used to interpret and analyse metabolites in the system. Significant changes will be noticed within every 24 hours at the start of the experiment hence samples need to be taken every 24 hours to trace the rate of metabolism activity taking place between the anode and cathode. Proceeding further with the experiments as days went by, it was noticed that there was very little change taking place in the system and sample where taken 36 – 48 hours when necessary, but refilling the cathode chamber with water happened frequently and this had to be done every 24 hours because of evaporating heating. While, the pH of the system was taken frequently, this helped in keeping a close eye on the systems operation because an increase or decrease in pH will have negative implications on power production. The MFC systems pH often dropped to 7 and was fluctuating between 7 – 7.5. For the project experiment they did not allow for the system to have a pH drop to 6.5 – 6.

During the experiment it was noticed that there was a decrease in volume from the anode chamber due to the 2mL samples they took to measure the COD levels, the small amount obtained via a pipette to find the pH readings, and also through evaporating heating. Hence, they had to add a small quantity of synthetic wastewater feedstock into the anode chamber to keep the volume constant throughout the experiments while frequently adding tap water into the ecobath to have the same quantity of water

through the experiment. Current density and power curves where drawn from the readings obtained and this allowed us to have a view as to the operations of the MFC system.

3.7 MFC sterilization

Sterilizing components is a major issue in MFC systems, as these experiments are operated for long period of time. And contamination may occur if there are sterilized for the next experiments, because not every feedstock culture medium will be the same. Hence, the anode and its compartments need to be sterilized separately also the cathode needs to be sterilized and everything within the system needs to be fresh and clean to allow an even experiment. The table below show sterilization techniques for components in the system.

Table 3.7 *– MFC component sterilization.*

Items Requiring Sterilization	***Method of Sterilization***
Anode Chamber	Washed with a multi-purpose cleaner using a brush, then rinsed with tap water and sterilize using distilled water.
Anode Electrode	Should be change for every experiment. *New electrodes are to be used
Cathode Electrode	Should be change for every experiment. *New electrodes are to be used
PEM	Should be change for every experiment. *New electrodes are to be used
Stainless Steel Mesh	Should be change for every experiment. *New electrodes are to be used
Gaskets	Washed with a multi-purpose cleaner using a brush, then rinsed with tap water and sterilize using distilled water.
MFC medium	A fresh new hatch of feedstock (synthetic wastewater) should be prepared.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter gives intensive results and discussions of the overall study of the project. Detailed results are discussed using tables and graphs.

Experiments were conducted using an MFC system, in order for us to determine any system parameters in the development of the current project. These experiments used a CMI-7000S PEM, and activated carbon which was pressed on a stainless-steel mesh.

4.2 Results

4.2.1 0% Uncoated carbon cloth

Table 4.1 shows the data obtained during the experiment to produce the power density and current density curves plotted on figure 4.2.1.1 till figure 4.2.1.3 for the 0% uncoated carbon cloth.

Table 4.1: *Results of the uncoated (0%) PTFE.*

	0% PTFE									
Resistance Number	Ohms	Voltage	Current (mA)	Temperature	pH	OCV	COD (Before)	COD (After)	Current Density (mA/cm^2)	Power Density (mW/m^2)
1	2400	0.074	0.0308						0.000856	0.6338
2	2200	0.078	0.0355						0.000985	0.7682
3	2000	0.083	0.0415						0.001153	0.9568
4	1800	0.086	0.0478						0.001327	1.1414
5	1600	0.087	0.0544						0.001510	1.3141
6	1400	0.086	0.0614						0.001706	1.4675
7	1200	0.085	0.0708	308K	7.1	0.057	110mg/L	79mg/L	0.001968	1.6725
8	1000	0.086	0.0860						0.002389	2.0544
9	800	0.085	0.1063						0.002951	2.5087
10	600	0.083	0.1383						0.003843	3.1894
11	400	0.082	0.2050						0.005694	4.6694
12	200	0.078	0.3900						0.010833	8.4500
	0	0.002	0.0000						0.000000	0.0000

Table 4.1 shows an OCV of 0.057V and a cell voltage of 0.074V on the start at an applied external resistance of 2400ohms. From the given table above the cell voltage increases with a decrease in resistance until a maximum level where it started to decrease. The cell voltage decreased to 0.078V at an external resistance of 200 Ohms.

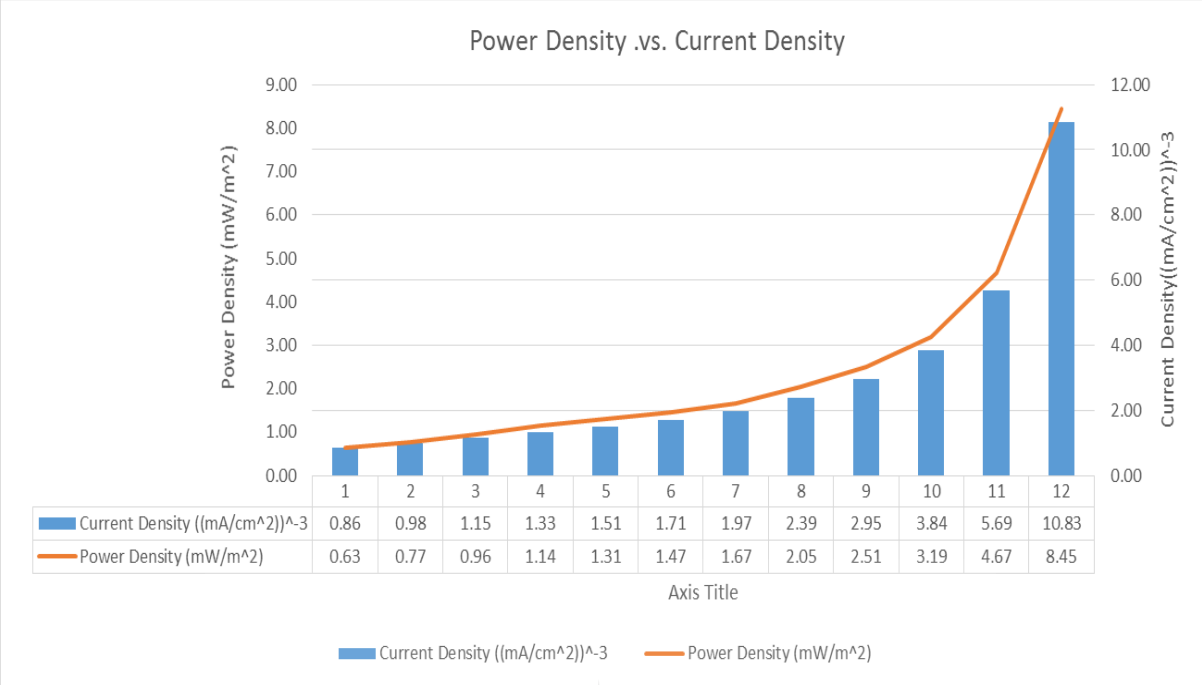


Figure 4.2.1.1 – *Power density vs Current density curves for (0%) uncoated carbon cloth.*

Figure 4.2.1.1 clearly shows that the maximum power density output of the 0% uncoated carbon cloth produced was 8.45mW/m^2 at a current density of 0.010833mA/cm^2 with fixed external resistance of 200 Ohms. The graph shows an increase of power density with an increase in current density. The polarization curve shows that as the power density increases so does the current density increase, until a maximum level where both the curves drop to their lowest with an applied external resistance of 0 ohms.

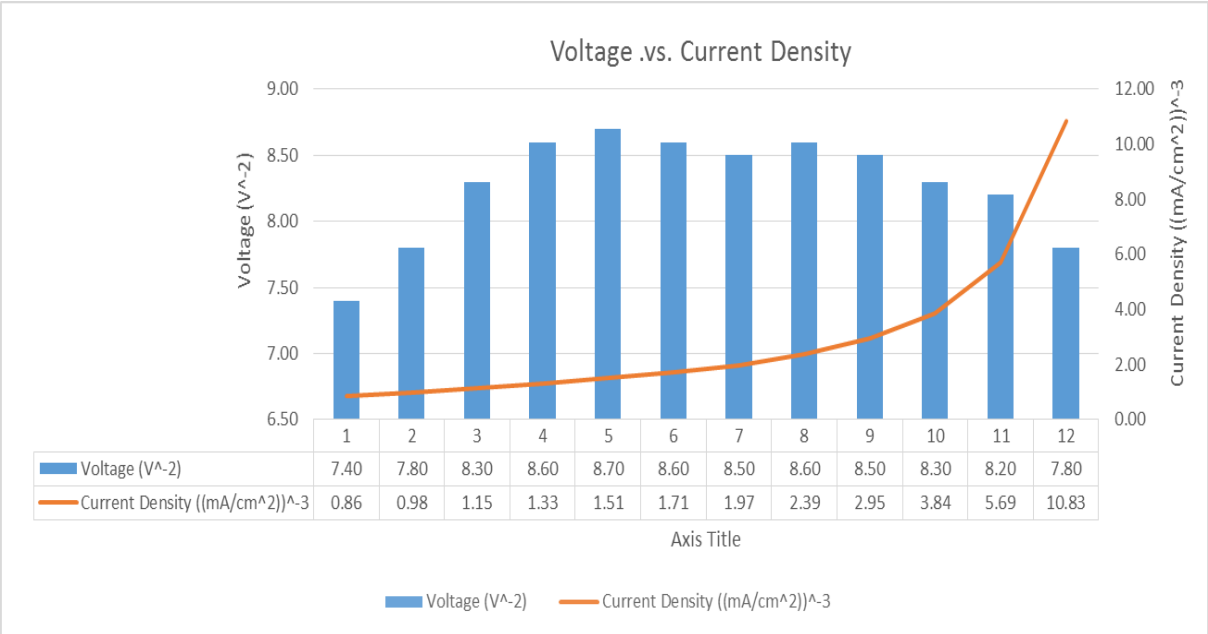


Figure 4.2.1.2 – *Voltage vs Current density curves for (0%) uncoated carbon cloth.*

Figure 4.2.1.2 clearly shows that the maximum voltage output of the 0% uncoated carbon cloth produced was 0.087V at a current density of 0.001510mA/cm^2 with fixed external resistance of 1600ohms. The graph shows an increase of voltage with an increase in current density, until a certain maximum point where the voltage was ranging with consistency. At 200ohms the voltage dropped to 0.078V while the current was at its highest at 0.3900mA.

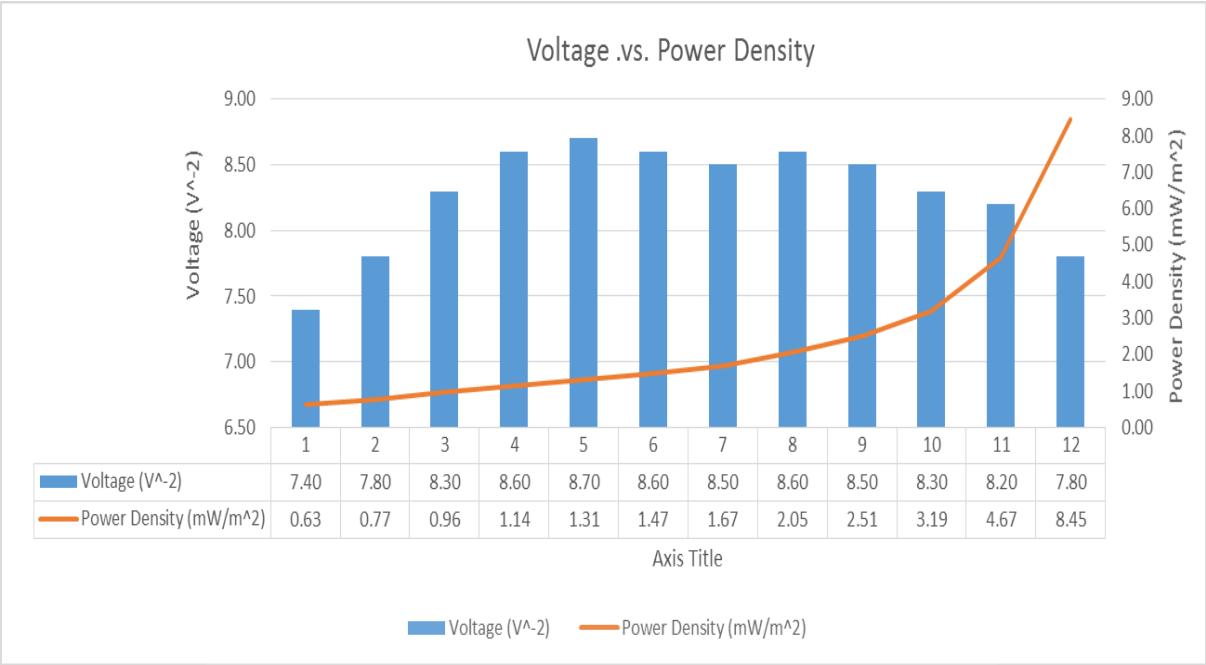


Figure 4.2.1.3 – *Power density vs Voltage curves for (0%) uncoated carbon cloth.*

Figure 4.2.1.3 clearly shows that the maximum voltage output of the 0% uncoated carbon cloth produced was 0.087V at a power density of 8.45mW/m^2 with fixed external resistance of 200ohms. The graph shows an increase of voltage with an increase in power density, until a certain maximum point where the voltage was ranging with consistency. At 200ohms the voltage dropped to 0.078V while the power density was at its highest at 8.45mW/m^2.

4.2.2 PTFE Coated (30%) Anode

Table 4.2 shows the data obtained during the experiment to produce the power density and current density curves plotted on figure 4.2.2.1 till figure 4.2.2.3 for the 30% PTFE coated carbon cloth. Tables and figures are presented below.

Table 4.2: *Results of the coated carbon cloth 30% PTFE.*

	30% PTFE									
Resistance Number	Ohms	Voltage	Current (mA)	Temperature	pH	OCV	COD (Before)	COD (After)	Current Density (mA/cm^2)	Power Density (mW/m^2)
1	2400	0.026	0.0108						0.000301	0.078241
2	2200	0.03	0.0136						0.000379	0.113636
3	2000	0.03	0.0150						0.000417	0.125000
4	1800	0.03	0.0167						0.000463	0.138889
5	1600	0.03	0.0188						0.000521	0.156250
6	1400	0.031	0.0221						0.000615	0.190675
7	1200	0.03	0.0250	307.1K	7	0.28	109mg/L	80mg/L	0.000694	0.208333
8	1000	0.029	0.0290						0.000806	0.233611
9	800	0.029	0.0363						0.001007	0.292014
10	600	0.029	0.0483						0.001343	0.389352
11	400	0.03	0.0750						0.002083	0.625000
12	200	0.029	0.1450						0.004028	1.168056
	0	0	0.0000						0.0000	0.000000

Table 4.2 shows an OCV of 0.28V and a cell voltage of 0.026V on the start at an external resistance of 2400ohms. From the given table above the cell voltage increases as the applied external resistance decreases. The cell voltage decreased to 0.029V at an external resistance of 200ohms.

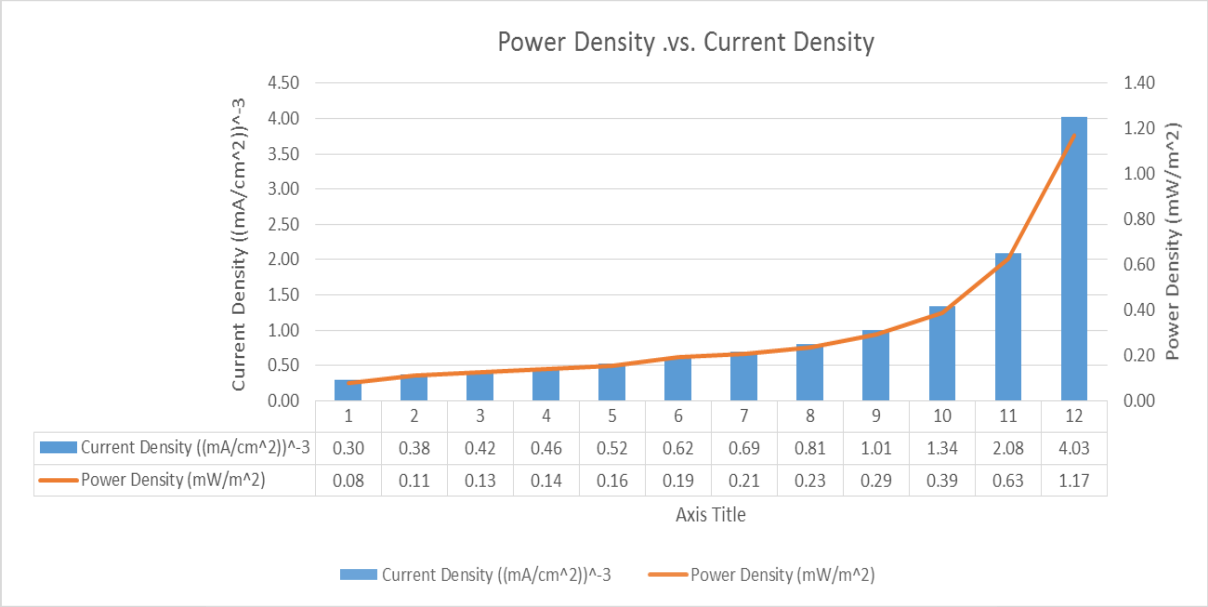


Figure 4.2.2.1 – *Power density vs Current density curves for 30% PTFE coated carbon cloth.*

Figure 4.2.2.1 clearly shows that the maximum power density output of the 30% PTFE coated carbon cloth produced was 1.168mW/m^2 at a current density of 0.004028mA/cm^2 with fixed external resistance of 200ohms. The graph shows an increase of power density with an increase in current density.

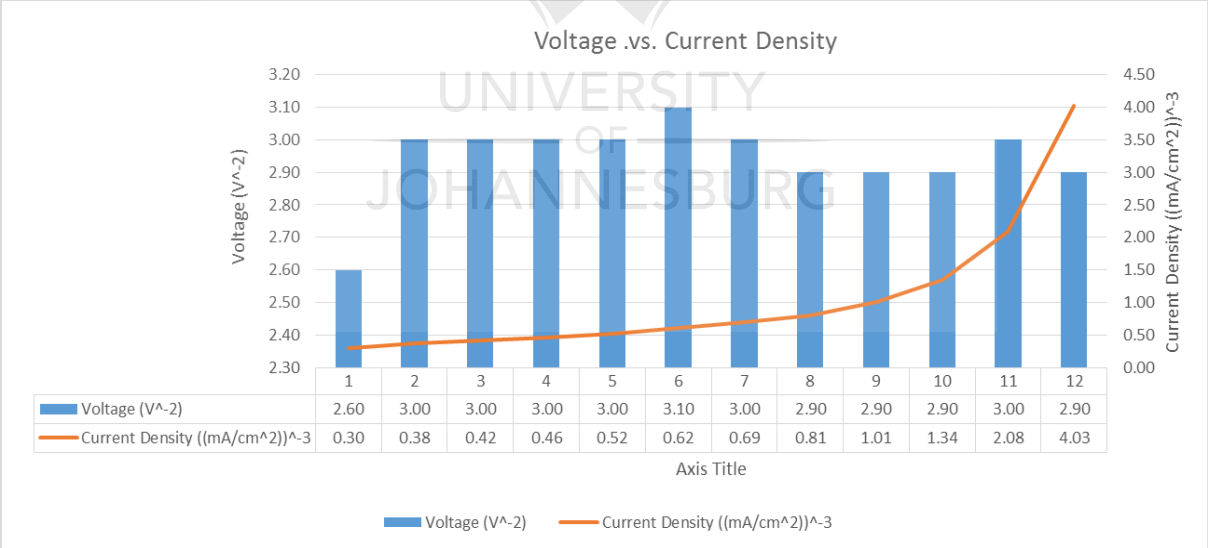


Figure 4.2.2.2 – *Voltage vs Current density curves for 30% PTFE coated carbon cloth.*

Figure 4.2.2.2 clearly shows that the maximum voltage output of the 30% PTFE coated carbon cloth produced was 0.031V and a current density of

0.004028mA/cm^2 with fixed external resistance of 200ohms. The graph shows an increase of voltage at a consistent range with an increase in current density.

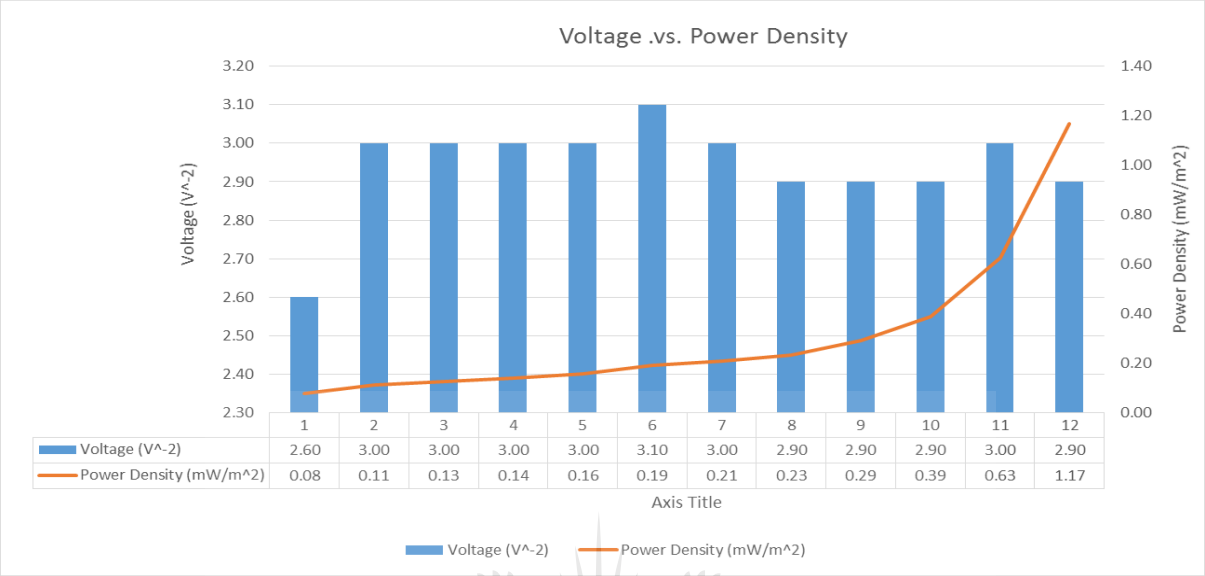


Figure 4.2.2.3 – *Power density vs Voltage curves for (30%) uncoated carbon cloth.*

Figure 4.2.2.3 clearly shows that the maximum voltage output of the 30% coated carbon cloth produced was 0.031V at a power density of 1.168mW/m^2 with fixed external resistance of 200ohms. The graph shows an increase of voltage with an increase in power density, until a certain maximum point where the voltage was ranging with consistency. At 200ohms the voltage dropped to 0.029V while the power density was at its highest at 1.168mW/m^2.

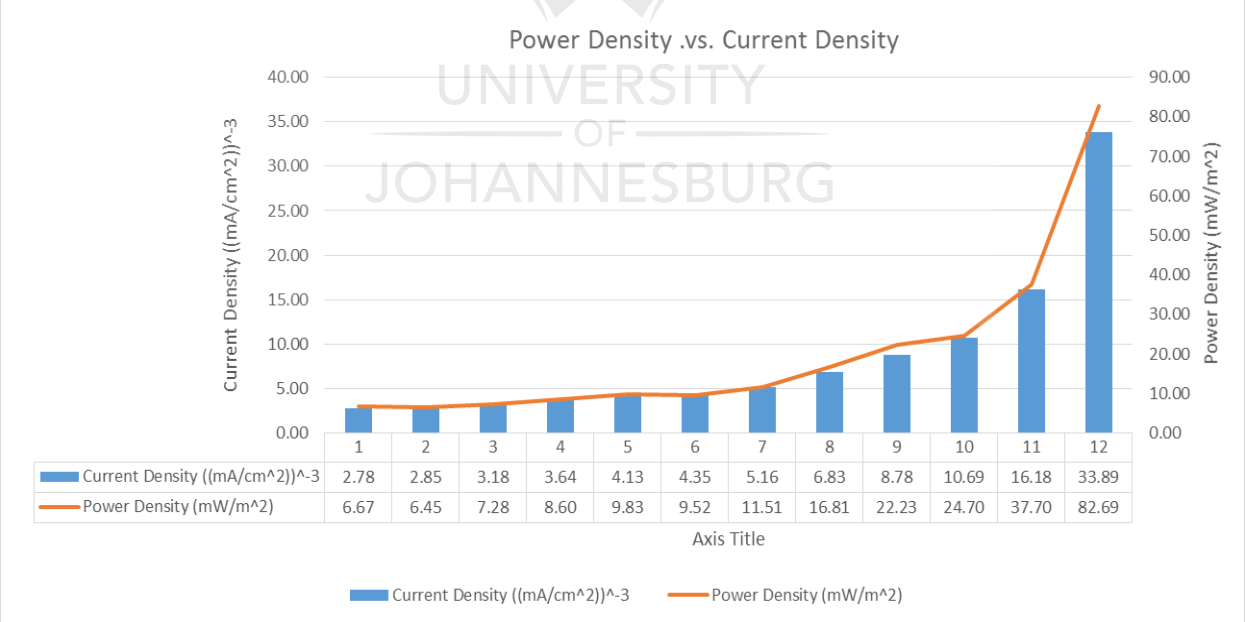
4.2.3 PTFE Coated (40%) Anode

Table 4.3 shows the data obtained during the experiment to produce the power density and current density curves plotted on figure 4.2.3.1 and figure 4.2.3.3 for the 40% PTFE coated carbon cloth. Tables and figures are presented below.

Table 4.3: *Results of the coated carbon cloth 40% PTFE.*

	40% PTFE									
Resistance Number	Ohms	Voltage	Current (mA)	Temperature	pH	OCV	COD (Before)	COD (After)	Current Density (mA/cm^2)	Power Density (mW/m^2)
1	2400	0.24	0.1000						0.002778	6.666667
2	2200	0.226	0.1027						0.002854	6.448990
3	2000	0.229	0.1145						0.003181	7.283472
4	1800	0.236	0.1311						0.003642	8.595062
5	1600	0.238	0.1488						0.004132	9.834028
6	1400	0.219	0.1564						0.004345	9.516071
7	1200	0.223	0.1858	308.2K	7.1	0.24	107mg/L	52mg/L	0.005162	11.511343
8	1000	0.246	0.2460						0.006833	16.810000
9	800	0.253	0.3163						0.008785	22.225347
10	600	0.231	0.3850						0.010694	24.704167
11	400	0.233	0.5825						0.016181	37.700694
12	200	0.244	1.2200						0.033889	82.688889
	0	0.002	0.0000						0.000000	0.000000

Table 4.3 shows an OCV of 0.24V and a cell voltage of 0.24V on the start at an external resistance of 2400ohms. From the given table above the cell voltage increases as the applied external resistance decreases. The cell voltage decreased to 0.002V at an external resistance of 0ohms.

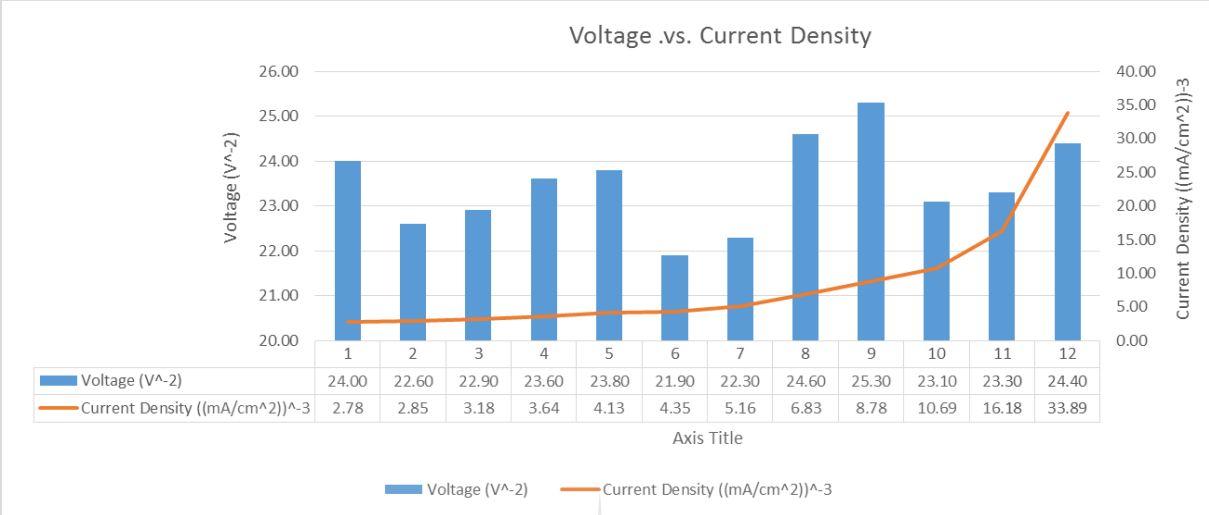


	1	2	3	4	5	6	7	8	9	10	11	12
Current Density ((mA/cm^2))^-3	2.78	2.85	3.18	3.64	4.13	4.35	5.16	6.83	8.78	10.69	16.18	33.89
Power Density (mW/m^2)	6.67	6.45	7.28	8.60	9.83	9.52	11.51	16.81	22.23	24.70	37.70	82.69

Figure 4.2.3.1 – *Power density vs Current density curves for 40% PTFE coated carbon cloth.*

Figure 4.2.3.1 shows that the maximum power density output of the 40% PTFE coated carbon cloth produced was 82.6889mW/m^2 at a current density of

0.0339mA/cm^2 with fixed external resistance of 200ohms. The graph shows an increase of power density with an increase in current density.



	1	2	3	4	5	6	7	8	9	10	11	12
Voltage (V^-2)	24.00	22.60	22.90	23.60	23.80	21.90	22.30	24.60	25.30	23.10	23.30	24.40
Current Density ((mA/cm^2))^-3	2.78	2.85	3.18	3.64	4.13	4.35	5.16	6.83	8.78	10.69	16.18	33.89

Figure 4.2.3.2 – *Voltage vs Current density curves for 40% PTFE coated carbon cloth.*

Figure 4.2.3.2 shows that the maximum voltage output of the 40% PTFE coated carbon cloth produced was 0.253V and a current density of 0.0339mA/cm^2 with fixed external resistance of 800ohms for the voltage and 200ohms for current density. Initially the graph indicates a decrease in voltage until it has ranged with consistency with an increase in current density until the maximum peak voltage, and then the graph shows a decrease of voltage with a decrease in current density.

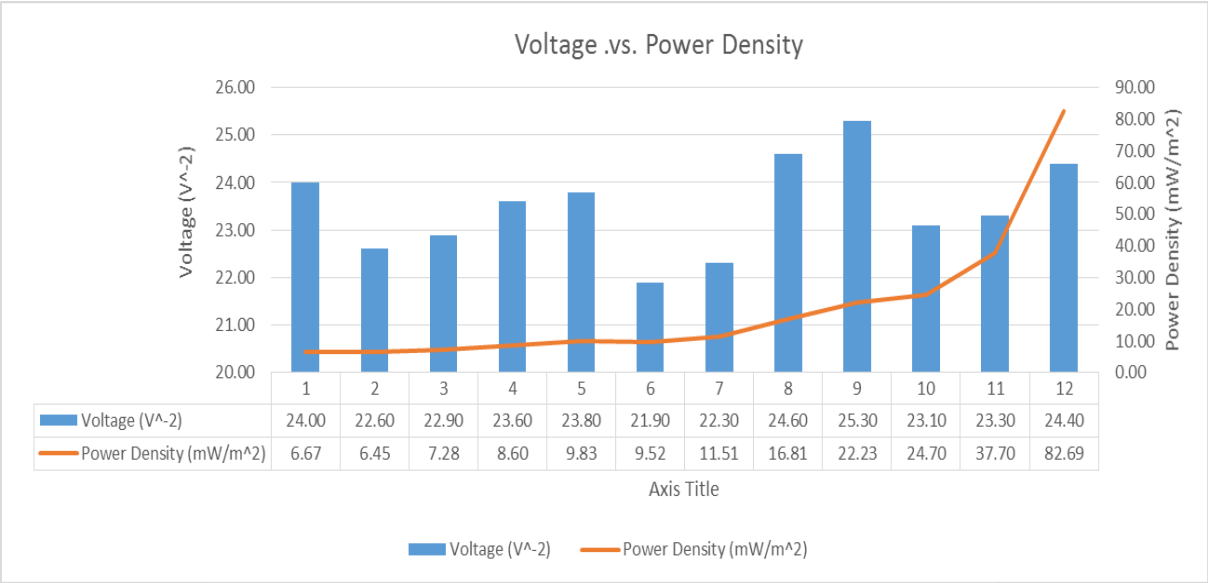


Figure 4.2.3.3 – *Power density vs Voltage curves for 40% PTFE coated carbon cloth.*

Figure 4.2.3.3 clearly shows that the maximum voltage output of the 40% coated carbon cloth produced was 0.253V at a power density of 82.6889mW/m^2 with fixed external resistance of 800ohms for the voltage and 200ohms for power density. The graph shows a decrease of voltage with an increase in power density, until a certain maximum point where the voltage was ranging with consistency. At 200ohms the voltage dropped to 0.244V while the power density was at its highest at 82.6889mW/m^2.

4.2.4 PTFE Coated (50%) Anode

Table 4.4 shows the data obtained during the experiment to produce the power density and current density curves plotted on figure 4.2.4.1 and figure 4.2.4.3 for the 50% PTFE coated carbon cloth. Tables and figures are presented below.

Table 4.4: *Results of the coated carbon cloth 50% PTFE.*

	50% PTFE									
Resistance Number	Ohms	Voltage	Current (mA)	Temperature	pH	OCV	COD (Before)	COD (After)	Current Density (mA/cm^2)	Power Density (mW/m^2)
1	2400	0.25	0.1042						0.002894	7.233796
2	2200	0.256	0.1164						0.003232	8.274747
3	2000	0.253	0.1265						0.003514	8.890139
4	1800	0.25	0.1389						0.003858	9.645062
5	1600	0.258	0.1613						0.004479	11.556250
6	1400	0.26	0.1857						0.005159	13.412698
7	1200	0.255	0.2125	308K	7.1	0.26	100mg/L	43mg/L	0.005903	15.052083
8	1000	0.264	0.2640						0.007333	19.360000
9	800	0.258	0.3225						0.008958	23.112500
10	600	0.253	0.4217						0.011713	29.633796
11	400	0.253	0.6325						0.017569	44.450694
12	200	0.25	1.2500						0.034722	86.805556
	0	0	0.0000						0.000000	0.000000

Table 4.4 shows an OCV of 0.26V and a cell voltage of 0.25V on the start at an external resistance of 2400ohms. From the given table above the cell voltage increases as the applied external resistance decreases. The cell voltage decreased to 0.25V at an external resistance of 200ohms.

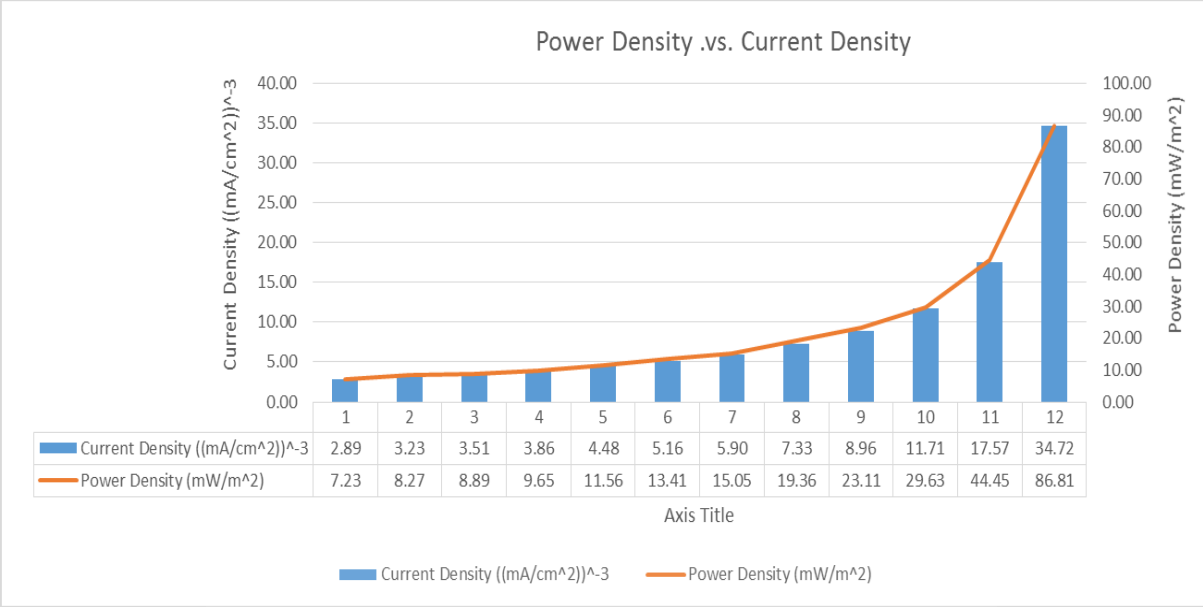


Figure 4.2.4.1 – *Power density vs Current density curves for 50% PTFE coated carbon cloth.*

Figure 4.2.4.1 shows that the maximum power density output of the 50% PTFE coated carbon cloth produced was 86.80mW/m^2 at a current density of 0.034722mA/cm^2 with fixed external resistance of 200ohms. The graph shows a decrease in power density and a decrease in current density when the external resistance is at 0ohms.

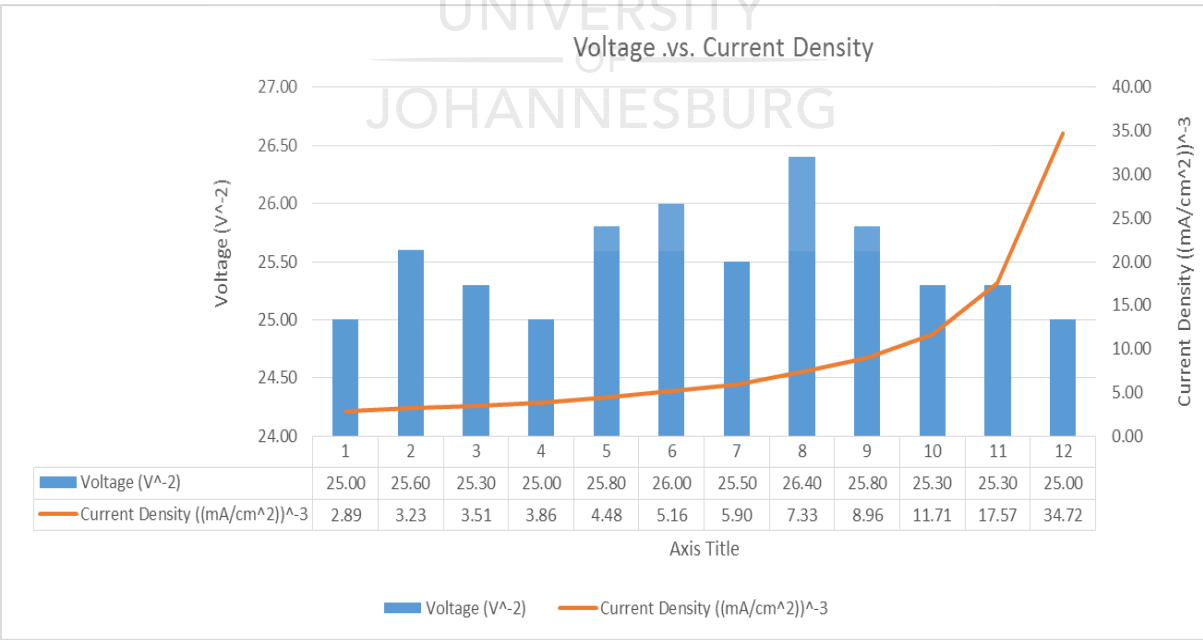
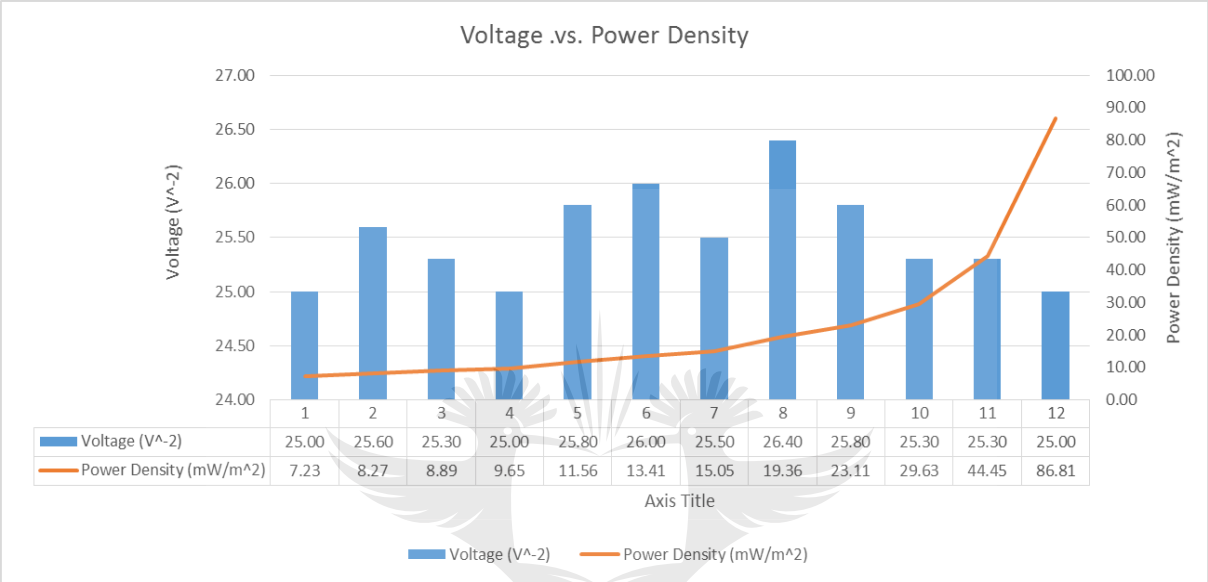


Figure 4.2.4.2 – *Voltage vs Current density curves for 50% PTFE coated carbon cloth.*

Figure 4.2.4.2 shows that the maximum voltage output of the 50% PTFE coated carbon cloth produced was 0.258V at an external load of 800ohms at an increasing current density of which had a maximum of 0.034722mA/cm^2 with fixed external resistance of 200ohms. Initially the graph indicates a decrease in voltage with an increase in current density.



	1	2	3	4	5	6	7	8	9	10	11	12
Voltage (V^-2)	25.00	25.60	25.30	25.00	25.80	26.00	25.50	26.40	25.80	25.30	25.30	25.00
Power Density (mW/m^2)	7.23	8.27	8.89	9.65	11.56	13.41	15.05	19.36	23.11	29.63	44.45	86.81

Figure 4.2.4.3 – *Power density vs Voltage curves for 50% PTFE coated carbon cloth.*

Figure 4.2.4.3 clearly shows that the maximum voltage output of the 50% PTFE coated carbon cloth produced was 0.258V at a power density of 86.80mW/m^2 with fixed external resistance of 800ohms for the voltage and 200ohms for power density. The graph shows a slight decrease of voltage with an increase in power density, until a certain maximum point where the voltage was ranging with consistency. At 200ohms the voltage dropped to 0.25V while the power density was at its highest at 86.80mW/m^2.

4.3 Discussion

From the results and tables above, the power densities increase with an increase in current density, the voltage also decreases with an increase in current but with comparison to the current density it can be stated that voltage decreases with an increase in current density.

For comparison between the different PTFE (0%, 30%, 40% & 50%) carbon coatings, the maximum power density output was produced from the 50% PTFE (86.80mW/m^2) than on the other coated PTFE carbon cloth. Hence, this indicates that the 50% carbon cloth performs much better than the other verify carbon coated PTFE.

The 50% coated carbon cloth produced the most power density Table 4.4 shows an OCV of 0.26V and a cell voltage of 0.25V on the start at an external resistance of 2400ohms. From the given table above the cell voltage increased as the applied external resistance decreases. The cell voltage decreased to 0.25V at an external resistance of 200ohms.

Figure 4.7 shows that the maximum power density output of the 50% PTFE coated carbon cloth produced was 86.80mW/m^2 at a current density of 0.034722mA/cm^2 with fixed external resistance of 200ohms. The graph shows an increase in power density and an increase in current density.

Figure 4.8 shows that the maximum voltage output of the 50% PTFE coated carbon cloth produced was 0.258V at a current density of 0.034722mA/cm^2 with fixed external resistance of 200ohms. Initially the graph indicates a decrease in voltage which remained at constant levels till maximum with an increase in current density.

Beyond a certain point (maximum power density output), the power drops due to certain constraints like Ohmic losses, electrode potentials and the mobility of microbes which are present to produce electrons in the anode and cathode. For comparison between all the verifying carbon cloths, can state that;

The 50% coated carbon cloth performed 90.2%, 98.6%, and 5% better than the 0%, 30%, and 40% respectively.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Introduction

This chapter covers the conclusions that were drawn based on the results obtained and analyzed, and the recommendations drawn from the conclusion to give a solution to the problem encountered throughout the course of the project.

5.2 Conclusions

The 50% PTFE coated anode generates the most power density output compared to the other carbon coatings

The 50% PTFE coated anode is more efficient in generating power than the others (0%, 30%, and 40% PTFE)

The performance of the individual coated carbon cloths varies significantly with the type of percentage coating which is applied on the cloth

The performance of the carbon cloth directly affects the overall performance of the microbial fuel cell

Currently there is not enough literature with regards to the performance of bioelectrochemical properties between the different coated carbon cloths

Activated carbon aided with the performance of power production in the system and allowed more power to be produced

5.3 Recommendations

1) Anode bacterial growth of microbes is active when the pH of synthetic wastewater is kept close to neutral, therefore the pH of the wastewater must be kept around the pH levels where the microbes are active for better results.
2) Fresh synthetic wastewater is needed for increasing the power output due to the active high concentrations of the microbes.

3) Further developments of present and new concepts with regard to coated carbon cloths and MFC performance should be done.
4) Water temperature should always be constant throughout the project.
5) Pulverize the activated carbon to different sizes, increasing surface area increases rate of reaction.

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