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Microbial Conversion of Biomass: A Review of Microbial Fuel Cells

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1. Introduction

The cleaner generation of energy is a vital concept if we are to ensure the survival of our current lifestyle past the depletion of the Earth's fossil fuel supply. The study described in this chapter investigates the alternative energy producing method of microbial conversion of biomass to produce electrical energy. Currently techniques are being explored to minimise the cost of building and running cells in which microbial conversion takes place. There are several areas where improvements may be made including the physical design of the cell, the catalyst used in the cathode chamber, the membrane material and the ideal low-cost substrate. The study presented in this chapter provides a review of Microbial Fuel Cells (MFCs), and discusses the design and construction of MFCs and presents the results of tests carried out with a number of constructed cells.

There is no doubt that the world's increasing population is rapidly depleting planet's finite energy resources. It is common knowledge today that the techniques developed to produce electricity and run our vehicles have also been leading to temperature rises resulting in climate changes all over the world. Currently, the world consumes approximately 13 Terawatts of power (Chae et al., 2009) every year while a mere 20 % of this is produced from renewable sources (Hopwood & Cohen, 2000). Techniques of harnessing energy from renewable sources are continuously being further developed all over the world, but are still yet to reach the efficiency levels, which would make these techniques comparable to the traditional, yet unsustainable coal-fired generation.

The discovery of a process in which bacteria are utilised in the fermentation of organic substrates to produce electricity can assist with the transition towards more sustainable ways of energy generation. This is the concept of a Microbial Fuel Cell (MFC). Later, it was also discovered that a variation of the MFC design could produce hydrogen instead through electrolysis. This was termed a Microbial Electrolysis Cell (MEC) (Logan, 2008).

Hydrogen is the most abundant element in the universe with more than 9 out of every 10 atoms being hydrogen atoms. Our most precious resource is made mainly of hydrogen. The Sun's gravitational force pulls hydrogen atoms together which releases helium and energy by the process of fusion. This energy is received on earth as the light and heat which sustains life on Earth. Hydrogen is recognised as an attractive energy carrier due to its clean, efficient and renewable nature (Chae et al., 2009) . It has applications in the production of

ammonia and methanol, the refining of metals and most recently as a clean fuel for powering vehicles. Hydrogen can be produced in a number of ways including as a by-product during the cracking of crude oil or by way of electrolysis in a diaphragm cell (Knapp, 2002). The majority of hydrogen gas produced today is developed from fossil fuels contributing to the release of carbon dioxide (Logan et al., 2008). An MEC improves on traditional hydrogen production technology by producing hydrogen yields many times greater than fermentation and at greater energy efficiencies than water electrolysis (Call & Logan, 2008; Logan et al., 2008).

Both MFCs and MECs have great potential in the renewable energy trend. As such many researchers across the world are investigating improvements to the two different systems. While the physical cell structures which can be used are the same, it is the reactions inside the cell which differ. In a microbial fuel cell, bacteria attached to the anode oxidise organic material releasing carbon dioxide and protons into the anode chamber solution. Electrons are transferred to the anode itself which then flow through an electrical circuit to the cathode where they are consumed in the reduction of oxygen. Meanwhile protons cross into the cathode chamber via a membrane. A current is therefore produced as there is a flow of electrons. However, in the absence of oxygen in the cathode chamber no current will be produced. This leads to the variations which constitute an electrolysis cell. With the addition of a small voltage between the anode and cathode, protons now become reduced at the cathode and hydrogen gas is produced (Logan et al., 2006; Call & Logan, 2008; Logan & Cheng, 2008). This process is known as electrohydrogenesis (Logan et al., 2008).

In an attempt to increase the power and hydrogen produced by MFCs and MECs respectively, researchers have recognized a number of areas where variations in design can be studied. Numerous papers have been published as to the effects of differing pH, temperature, electron acceptor, electrode surface area, reactor size and electrode and membrane material (Logan et al., 2008). Many carbon and graphite electrode materials from carbon paper to graphite pencil leads have been trialled with the common conception that graphite brushes produce the best results due to their large surface area (Logan, 2008). Reactor designs are limited only by the imagination and many variations of the original two bottle design have emerged including single chamber, cube, cylinder and U-shaped reactors.

A review of MEC technology has identified several research areas that must still be addressed before MECs can be considered a mature hydrogen production method. These observations are:

- More experience is required with real organic feed stocks containing complex organic substrates such as polymeric and particulate substances;
- Novel, more cost-effective chemical and/or biological cathodes need to be developed that show low potential losses and are not platinum-based;
- Membrane pH gradients need to be eliminated, or membranes should not be used in the reactor;
- Methanogenic consumption of the hydrogen product needs to be prevented (in the case of membrane-less MECs and/or MECs with a biocathode); and, most critically,
- A cost-effective, scalable MEC design needs to be developed.

As mentioned above, often cathodes are platinum based (He & Angenent, 2006; Logan & Cheng, 2008). The platinum acts as a catalyst and is necessary to enhance the rate of reduction of oxygen at the cathode (Logan et al., 2008). As platinum is highly expensive and can be poisoned by components of the substrate solution (Logan et al., 2008; You et al., 2009)

it is desirable to eliminate it from MFCs and MECs altogether. Several alternatives have been investigated including chemical catholytes, biocathodes and transitional metals (He & Angenent, 2006). Thus far the highest power ever achieved in an MFC has been using a ferricyanide cathode (He & Angenent, 2006). In order to minimise costs and work towards the eradication of platinum potassium permanganate has been used at the cathode.

2. Problem analysis

There are two significant energy related challenges facing the world. The first one is the production of cleaner, renewable energy at high efficiencies and low costs, the other, the consideration of efficient storage techniques for excess or intermittently produced electricity. Although renewable forms of energy have no or little negative environmental impacts they can have negative social, economical and technical problems associated with them. Wind turbines for instance create cleaner and renewable energy but are extremely expensive to set up and maintain. There are also social issues regarding their location as many people find them to be noisy and unattractive. Hydropower is one of the cleanest forms of renewable energy but it too is bound by locations problems. Hydropower requires suitable dam locations and most importantly, large amounts of water, something that many countries including Australia cannot provide. Solar power again is expensive and suffers low efficiencies while also having environmental effects. Solar panels require large amounts of energy to be produced and silicon production has recently led to unsafe toxic waste disposal. A potential solution to many of these problems are the fuel cells. They are highly efficient, reliable, are noiseless, emission-less and run on widely available fuels.

One problem with several forms of renewable energy is that it is produced intermittently, that is power is only produced at certain times not continuously. Such generation techniques include photovoltaic solar power and wind turbines as they both rely on the natural phenomena of sunlight and wind respectively. For these technologies to be viable options to replace less environmentally friendly generation methods the energy produced during generation periods must be able to be stored for use when generation is not possible. For example, solar power cannot be generated at night or in periods of low sunlight levels however the energy produced on sunny days could be stored and then used at these times. Many forms of energy storage exist including mechanical, chemical, thermal, electrochemical, electrical and biological storage. Other forms of clean, renewable energy are unaffected by environmental factors and can produce electricity constantly. These forms include hydropower, geothermal and fuel cells to name a few.

As previously mentioned, some renewable energy generation techniques require the energy to be stored for later use, in fact this is considered one of the biggest challenges affecting the solar power industry (Zyga, 2009). Electric cars are also being held back by the lack of appropriate storage techniques as batteries are heavy and inefficient when compared with fuels like petrol and gasoline (HowStuffWorks.com, 2000). World energy consumption is predicted to rise 44 percent over the next twenty years with green house gas emissions increasing a staggering 39 percent (Finfacts-Team, 2009). Obviously, this will have significant impact on climate change and put pressure on the power industry to cope with the increasing demand. Already high demand puts strain on the industry, not to mention on the customers wallets. Peak energy periods usually incur a higher cost to consumers.

The power grid also experiences problems of over-demand in extreme weather conditions where the use of heaters/air conditioners is extremely high. This generally results in power

outages for long periods of time. In the United States 14 percent of the country's power plants and known as "peaking plants," expensive gas turbines that are only operated during rare hours of extremely high demand (Plumer, 2009). This is an instance of where efficient, cost effective storage methods are highly desirable. The use of renewable generation techniques is predicted to increase throughout the world to contribute to the populations growing energy needs. Therefore, there will also be a greater need for energy storage to facilitate the continuous use of energy from intermittent sources.

3. Possible solutions

This section presents a review of different types of fuel cells and a comparative analysis in terms of design and construction difficulty, material expenses and potential efficiencies. The two main cells chosen are Hydrogen and Microbial Fuel Cells. Viable options are considered for all the necessary components including; a membrane, electrodes and a catalyst as well as possibilities for reactor configurations and substrates.
Several solutions to designing a clean energy storage device have also been evaluated for their suitability to store the electrical energy produced by the fuel cell. The energy can be stored in many forms such as kinetic, chemical, electrochemical and electrical. These types of energy storage have all been reviewed as candidates. The required solution must again prove to be of reasonable expense and effort to design, build and implement.

3.1 Fuel cells

A fuel cell is a device that is capable of converting the chemical energy in a fuel and an oxidant into electricity and a clean by product (FCTec, 2010). Fuels can consist of traditional compounds like hydrogen, natural gas, methanol and gasoline while a common oxidant is oxygen. A fuel cell is an electrochemical system like a battery however a fuel cell does not run down or need recharging; as long as a fuel and oxidiser are present the cell will generate electricity.
All fuel cells are constructed and operate in the same general manner. Figure 1 shows a cell that consists of three materials sandwiched together, namely an anode, electrolyte and cathode. The anode and cathode are known as electrodes and are made of some form of conductive material. The anode and cathode are where the oxidation of the fuel and reduction of the oxidant occur respectively. This is facilitated by a catalyst, which can consist of a range of substances. When the fuel is oxidised, electrons and protons are produced. The protons are able to flow through the electrolyte as it is a substance that allows ion exchange while electrons are blocked. Electrons therefore pass through the anode and to the cathode via an external circuit where they react with the protons and oxidant. This results in a by-product (usually water), while the flow of electrons constitutes an electrical current and therefore electricity generation.
Fuel cells are suitable for a wide range of applications. They are particularly useful as power sources in remote locations such as spacecraft, remote weather stations, rural locations, and even have military applications. Currently the use of fuel cells in cogeneration is a rapidly growing area for office buildings and factories. The advantage of homes and businesses using fuels cells is the savings on grid electricity and that excess energy produced can even be sold back to the grid for profit. Future prospects for the technology includes powering road and sea vehicles, providing off-grid power supplies and emergency power, micro fuel cells to implement in small appliances and as portable charging docks.

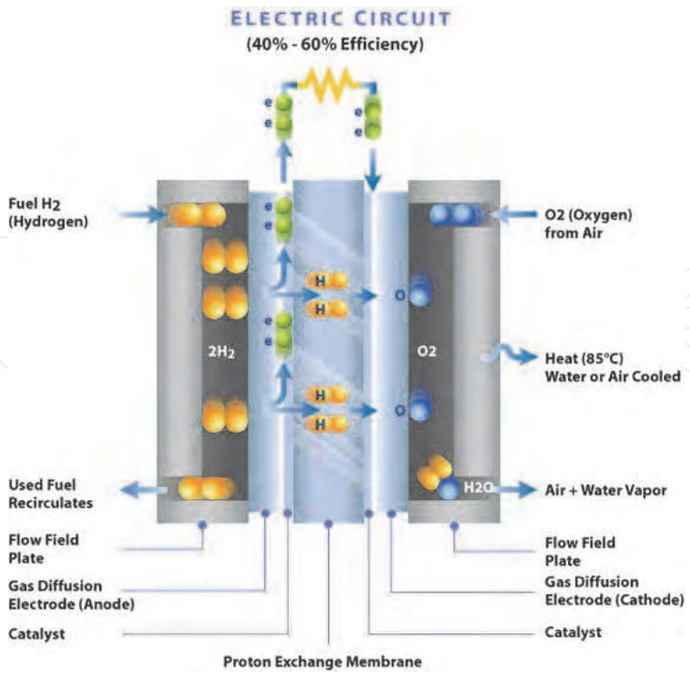

Fig. 1. Basic configuration of a fuel cell (Ballard Power Systems)

3.1.1 Hydrogen fuel cell

The most common form of fuel cell is the hydrogen fuel cell. In this case hydrogen is the fuel and oxygen is the oxidant. Pressurised hydrogen gas enters the anode chamber and is forced through a catalyst (usually platinum) by the pressure. When hydrogen comes in contact with the platinum it is split into two H+ ions and two electrons. Electrons conduct through the anode and to the cathode via an external circuit. Meanwhile in the cathode chamber oxygen gas is also forced into the catalyst where it splits into two strongly negatively charged oxygen atoms. The strong negative oxygen atom charge attracts the positively charged H+ ions through the membrane where they combine with the oxygen atoms and the electrons to form a water molecule (Nice & Strickland, 2010).

Design's can be as simple as using two pieces of platinum coated wire in a glass of water (Field, 2008) however platinum is extremely expensive and the source of fuel also presents difficulties. Water can be used as the source of hydrogen but there must be a way of splitting the atoms to release the hydrogen and oxygen atoms. This process is known as electrolysis and requires energy. Alternatively stored hydrogen and oxygen gas can be pumped into the cell. Efficiencies achieved can be up to 80% (Nice & Strickland, 2010).

3.1.2 Microbial fuel cell

A microbial fuel cell utilises the electron extracting properties of special bacteria attached to the anode to produce electricity. Bacteria attached to the anode oxidise organic material releasing carbon dioxide and protons into the anode chamber solution. Electrons are transferred to the anode itself which then flow through an electrical circuit to the cathode where they are consumed in the reduction of oxygen. Meanwhile protons cross into the cathode chamber via a membrane. A current is therefore produced as there is a flow of electrons.

A range of alternatives are available for all components while a range of organic material can be used as the cell's fuel. One option is to use wastewater in the anode chamber. This has the added benefit of water purification while electricity is produced. There is also no need to deal with hard to store gases such as hydrogen which are also expensive to produce. Organic matter can be sourced simply from household food scraps or garden waste. This makes a microbial fuel cell easy and inexpensive to run. Alternative catalysts are available to platinum which significantly reduces cell costs. Efficiencies achieved are comparable to those achieved with hydrogen fuel cells.

3.2 MFC components

An MFC requires much the same components as any other fuel cell however there are some drastic differences. Most obvious is the requirement for bacteria which is not an addition to any other type of fuel cell. Where most other fuel cells incorporate chemicals to achieve their electricity producing reactions, a microbial fuel cell requires a form of organic matter (substrate) to maintain the bacteria also providing the means of generation. Reactions using oxygen as the terminal electron acceptor are extremely slow so either a catalyst must be used or a terminal electron acceptor with a faster reaction time must replace oxygen in the cathode chamber. These alternatives for these things, along with the more conventional components; membrane and electrodes as well as reactor configuration, are discussed below.

3.2.1 Reactor

Reactor configurations vary greatly from researcher to researcher. The size and shape of a reactor is entirely up to the designer and as no stand out design has been identified the variations continue with the goal of finding a scalable design. To date reactors have been cube shaped, cylindrical, horse shoe shaped, two chamber and single chamber and H-type configured and made of glass and various types of plastic, even buckets. Sizes also vary widely with some reactors having volumes of a few square centimetres and others of up to a square metre. So far researchers have speculated that single chamber reactors may show the most promise but this has not deterred people from using two chamber types. In terms of construction difficulties a single chamber reactor can be the harder of the two options. For this reason the reactor for this research project will be a two chambered cell and to further simplify the design and construction a cube shape will be used. Figure 2 depicts the proposed cell design. The total reactor capacity will be 1.1L, 600mL in the anode chamber and 500mL in the cathode chamber.

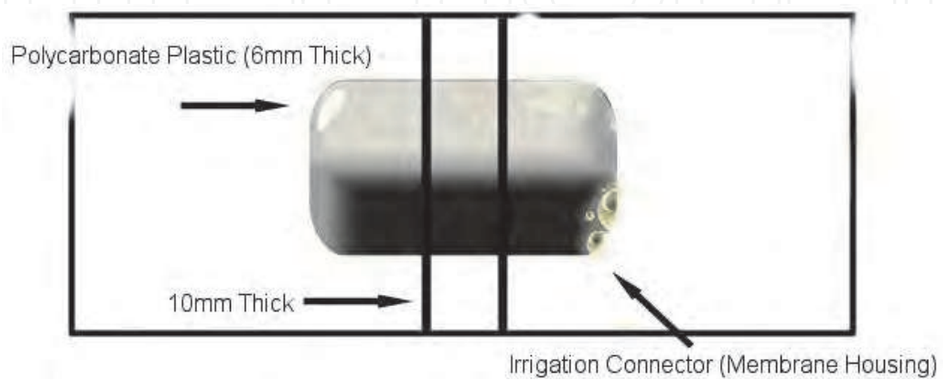

Fig. 2. Basic reactor design

3.2.2 Membrane

A membrane is described as a layer of material which serves as a selective barrier between two mediums that is impermeable to specific particles, molecules or substances. Membranes occur naturally in the bodies of plants and animals and are made artificially for separation purposes in laboratories and industry. Synthetic membranes include anion exchange membranes, cation exchange membranes and ultra filtration membranes. Studies have shown that anion exchange membranes perform better than cation exchange membranes due to a lower resistance (You et al., 2009) . These types of membranes are generally very expensive, have high minimum orders or incur large freight charges as they are only manufactured overseas. An alternative is membrane inclusive water resistant clothing such as Gore-Tex. High quality ski clothing is specially made to contain a membrane within the fabric to repel water. The fabric is suitable for fuel cell applications as it successfully separates the liquids in the two chambers whilst allowing protons to flow from the anode to the cathode chamber. Table 1 contains several membrane alternatives that would be suitable for the microbial fuel cell.

Company	Product	Description	Size (cm)	Price (AUD)	Freight (AUD)	Total (AUD)
FeMa Tech Germany	F-930–EW900 Thickness 30	Ion exchange membrane	20 x 30	$101.64	$73.653	$175.29
Fuel Cell Store	Nafion RE212	Proton exchange membrane	10 x 10	$26.17	$163.89	$190.06
Entrant	Ski Pants	Fabric sourced from pants	20 x 20	Free	$0	$0
Membranes International	AMI-7001S	Anion exchange membrane	15 x 15	Free	$0	$0

Table 1. Membrane solutions

3.2.3 Electrodes

All fuel cells require two electrodes, an anode and a cathode. These electrodes facilitate the transport of electrons through an external circuit hence resulting in electricity. Electrodes can be made of any non corrosive, conductive material. Most commonly used materials include carbon, graphite and steel. Steel has been found to be less effective for use in microbial fuel cells as it is not a porous material and bacteria appear to be unable to attach themselves (Logan, 2008) . Carbon and graphite are both widely available materials which come in many forms. Carbon is available as paper, cloth and foam while graphite comes in the form of rods, granules and brushes. Studies have not shown a distinct favourability towards neither carbon nor graphite so we will assume that performance is very similar and depends more heavily on electrode surface area. All above mentioned products are quite expensive and almost entirely produced overseas so there is also a high freight cost involved. Several companies were found to offer free samples of carbon foams and cloths however only one company does not charge a shipping cost for the sample. For this reason vitreous reticulated carbon foam has been chosen for the electrodes. Foam has an advantage over paper and cloth as it is more porous and has a greater surface area to house more bacteria.

3.2.4 Substrate

A substrate is the substance contained in the anode chamber that is to be oxidised. As mentioned earlier this can include fuels such as hydrogen and gasoline. In a microbial fuel cell the substrate used can be any form of organic matter. Cells have been successfully operated on chocolate (Markusic, 2010) , wine (Danigelis, 2009) , wastewater (Logan, 2008) , acetate (Liu et al., 2005; Sun et al., 2008), glucose (Logan, 2008) and more. Most frequently glucose, wastewater and acetate are used in experiments with the highest results being obtained with acetate (Logan, 2008) .

3.2.5 Catalyst/catholyte

The cathode chamber is where protons and electrons recombine and reduce an electron acceptor. A common electrode acceptor is oxygen due to its abundance in air. When oxygen is used however the reaction is very slow therefore the need for a catalyst arises. Most MFC's use platinum as the catalyst (Logan, 2008) however this is extremely expensive. Due to the expense, which affects the viability of fuel cells, much research is aimed at finding an equally efficient but less expensive catalyst. One option is to use a catholyte to replace oxygen as the terminal electron acceptor. Chemicals such as ferricyanide and potassium permanganate have been used successfully with results comparable to those achieved with platinum (He & Angenent, 2006). These chemicals are far less expensive than platinum however the disadvantage is that they are consumed in the reaction and must be replaced. Research has also been conducted into the use of bacterial cathodes known as biocathodes. The concept of a biocathode is that bacteria are attached to the cathode as they are to the anode. Bacteria then assist the reduction of oxygen without the need for any additional chemicals or substances (He & Angenent, 2006).

3.3 Common storage techniques

Energy storage is not a new development in fact people have been storing energy far before the discovery of electricity. Energy storage can be achieved in many ways; some techniques are simple such as those used in grandfather clocks while others involve complex chemical reactions.

3.3.1 Mechanical (flywheel)

A flywheel is a form of mechanical storage that far predates any battery; in fact it is one of humanities oldest and most familiar technologies. Examples are the potter's wheel which dates back six thousand years and more relevantly today the mechanism regulating the strokes of pistons in a car engine. A flywheel is simply a wheel on an axle which is able to store and regulate energy by continuously spinning. When spun at high speeds a fly wheel becomes a bank for massive amounts of kinetic energy which can be drawn out when required. Fly-wheel based batteries can reach energy densities 3-4 times higher than traditional lead-acid cell batteries. Another advantage of flywheels is that they are able to charge to full capacity in a matter of minutes rather than hours and discharge quickly without damage. They are also unaffected by extreme temperatures and have an impressive efficiency of 85-95% as well as a lifetime in decades (Putnam, 2007). A flywheel may not be appropriate to store the energy produced by the fuel cell in this project due to safety concerns associated with them caused by the high speed rotor. There is a possibility of the rotor breaking loose and releasing energy is an uncontrolled fashion (Rayner, 2008). They also experience a high current loss.

3.3.2 Electrochemical (battery)

A battery is a form of electrochemical energy storage, storing chemical energy and converting it to electrical energy. Chemicals inside the battery produce electrons which cling to the negative terminal. When the negative terminal is connected to the positive terminal via a conductor, electrons flow from the negative terminal to the positive terminal releasing their energy to a load. A battery is charged by doing the reverse of this action and applying an electrical current to the terminals. The disadvantage of batteries is that they are expensive and also heavy. This causes a significant problem for electric vehicles as weight is an important limiting factor in vehicle speed. One application of fuel cells is as an alternative to gasoline. For this reason batteries are not a suitable option for the storage of power from the fuel cell in this project.

3.3.3 Chemical (hydrogen)

Hydrogen is the most copious element in the universe with more than 9 out of every 10 atoms being hydrogen atoms. In fact our most precious resource is made mainly of hydrogen. The Sun's gravitational force pulls hydrogen atoms together which releases helium and energy by the process of fusion. We receive this energy as the light and heat which sustains life on Earth. Hydrogen is recognised as an attractive energy carrier due to its clean, efficient and renewable nature (Chae et al., 2009) . It has applications in the production of ammonia and methanol, the refining of metals and most recently as a clean fuel for powering vehicles. Hydrogen can be produced in a number of ways including as a by-product during the cracking of crude oil or by way of electrolysis in a diaphragm cell (Knapp, 2002) . The majority of hydrogen gas produced today is developed from fossil fuels contributing to the release of carbon dioxide (Logan et al., 2008). Hydrogen can also be produced by a process called electrolysis using either a hydrogen electrolysis cell or a microbial electrolysis cell. A Microbial Electrolysis Cell improves on traditional hydrogen production technology by producing hydrogen yields many times greater than fermentation and at greater energy efficiencies than water electrolysis (Call & Logan, 2008; Logan et al., 2008).

Hydrogen is a good storage option for this project and a microbial electrolysis cell is a suitable addition because it is closely related to the project fuel cell. The efficiencies of this storage technique are also very high. As such this will be suggested as the most suitable storage system to use.

4. Design and construction

This section outlines the design process, construction and testing of two MFC designs. The design process is explained in detail, construction strategies given, and results presented.

4.1 Design 1

Fuel cell design is an important factor in the success of an MFC/MEC. Single chamber cells have evolved from the original two chamber design in an attempt to eliminate the need for a membrane (Call & Logan, 2008). This is desirable to simplify reactor architecture and reduce the internal resistance caused by the inclusion of a membrane between chambers. It is also possible to lower the internal resistance of a two chamber cell by reducing the physical distance between the anode and cathode and increasing the area of the membrane. This is where the two bottle 'H-type' design falls short (Logan et al., 2008) and where cube and cylinder models show improvements. The prototype constructed in this experiment is a cube design for this reason.

4.1.1 Design and construction

The cell is constructed of a sturdy polycarbonate plastic with the anode chamber holding 600mL, slightly more than the cathode chamber which holds 500mL. The cell is airtight for use in MEC mode having just four valves which allow for helium to be flushed into both chambers, carbon dioxide to be removed from the anode chamber and hydrogen to be extracted from the cathode chamber. Figure 3 is a two dimensional, not to scale representation of the cell before any electrodes are incorporated.

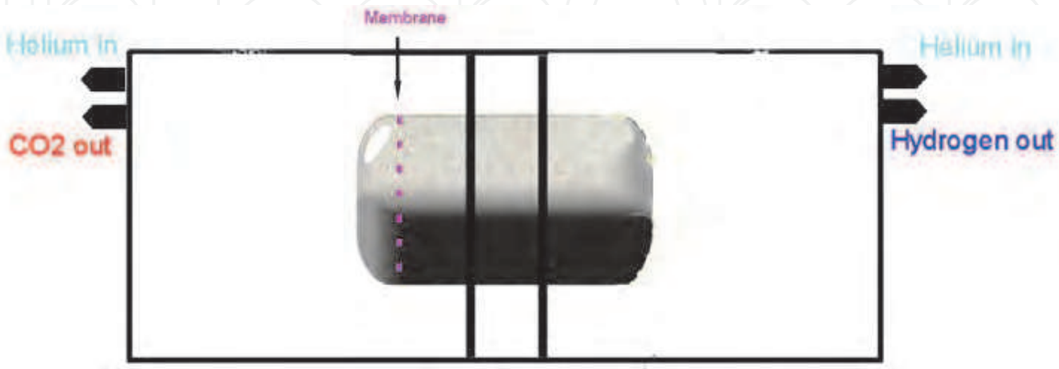

Fig. 3.Two dimensional conceptual model of the fuel cell without electrodes

The original complete reactor design is shown in Figure 4. As shown in the figure, the electrodes used are reticulated vitreous carbon foam. These are suspended from the lid of the cell by metal clips which attach to an external circuit containing a ten ohm resistor outside the cell. The membrane is a common ski clothing material known as Entrant. The material has been designed specifically as wet weather gear as the fabric contains a waterproof membrane. The fabric is suitable for use as a membrane as it will allow protons to pass through while preventing the contents in the two chambers from contaminating one another. Similar materials such as Gore Tex have also been shown to be effective as fuel cell membranes (Blair, 2008).

The membrane is held in place by an irrigation pipe fitting allowing a circular area of 3.5 cm for proton flow. The total cost of essential materials is AUD$57.55 for the MFC setup and $68.59 for the MEC setup (not including the cost of an inert gas for oxygen removal). Figure 5 is a photograph image of the finished reactor.

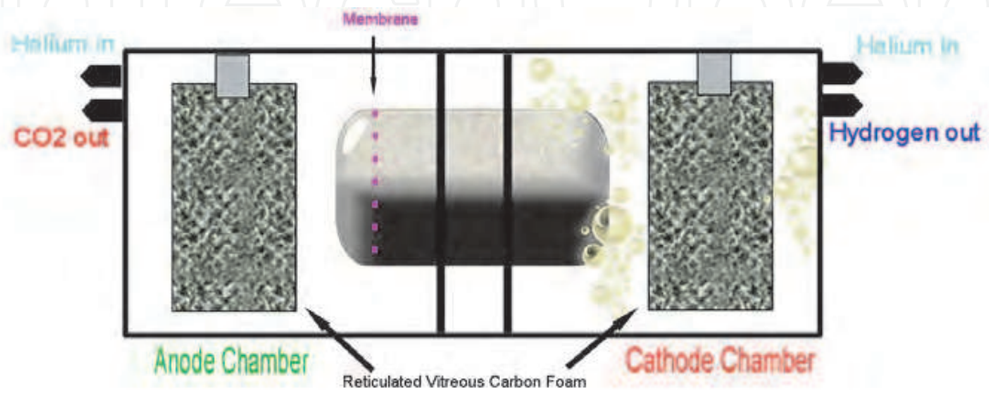

Fig. 4. Two dimensional diagram of complete fuel cell

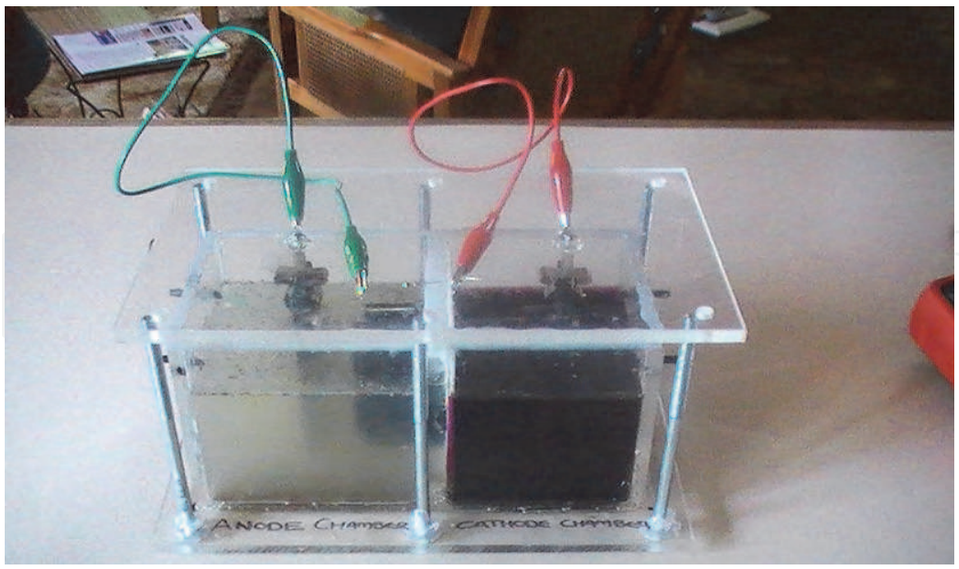

Fig. 5. Photographic image of the designed and constructed cell

Each chamber contains an inexact buffer solution to stimulate bacteria growth. Due to limited chemical resources where a precisely measured buffer solution would otherwise be used, fertilisers containing the necessary elements were added to each chamber. The anode was inoculated over 12 hours with water from the Maribyrnong River to allow time for the bacteria to attach to the electrode. The anode chamber was then filled with 300mL river water, the buffer ingredients and 300mL vinegar as the substrate. The cathode chamber contained only filtered water and the nutrients. The cell was then left over a period of 9 days to allow for bacterial growth.

4.1.2 Results and discussion

The cell was firstly operated in the MFC mode over a period of 90 hours with potassium permanganate used as the electron acceptor. At the instant of adding the catholyte the system produced 1.7mV. Measurements were taken as frequently as was possible without a system in place for automatic sampling. The recorded voltages and calculated current densities for this period are shown in Figure 6. The cell was not kept under temperature controlled conditions and it was observed that the voltages increased and decreased throughout the days with the fluctuating temperature. To investigate this more closely between the period of 64 and 76 hours from start both the voltage and temperature were recorded every fifteen minutes as shown in Figure 7.

The maximum voltage obtained throughout the cell running time occurred during this period. At 74.5 hours from start a voltage of 28.7mV was observed at a temperature of 39˚C. The corresponding current density is 404.8mA/m^2 with power normalised by anode surface area of 11.62mW/m^2 and volumetric power 50.05mW/ m^3. The system failed to produce hydrogen when operated as an MEC. Further experimentation is needed to determine if the reason for this was due to the presence of oxygen despite the cell being flushed with helium or due to the short running time and therefore lack of highly developed bacterial communities.

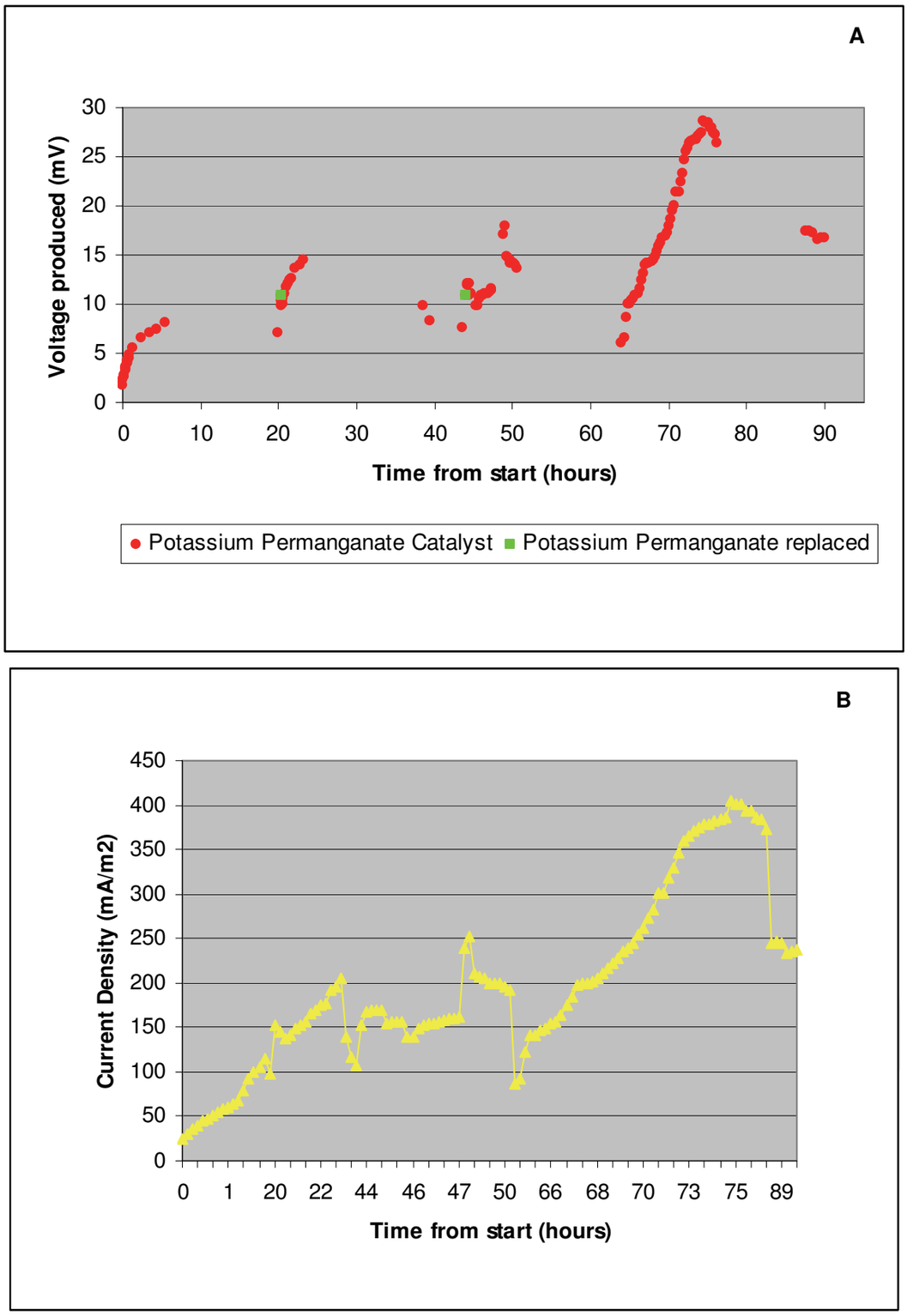

Fig. 6. A) Recorded voltages from start time (Oh) to end time (90h) and B) calculated current densities over the same period.

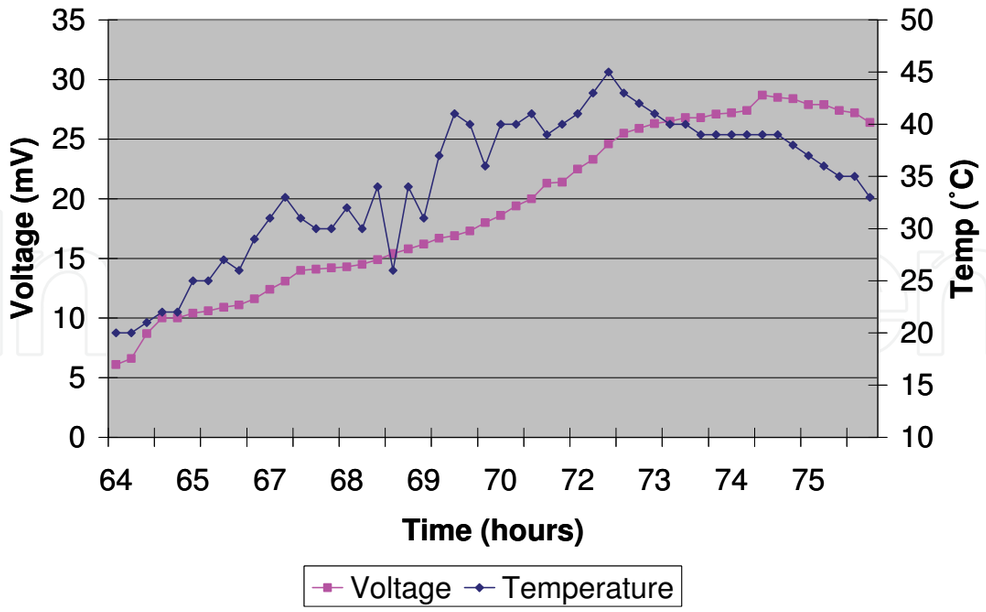

Fig. 7. Effect of varying temperature on voltage produced for the period 64 to 76 hours after start.

4.2 Design 2

Many possibilities could be identified to explain the low performance of the cell. The most obvious ones are the high internal resistance, inadequate bacterial growth and unsuitable/insufficient organic matter present. A combination of these may even have been the case.

4.2.1 Design and construction

In order to overcome the original cells problems several improvements were proposed. These included replacing the Entrant material with an anion exchange membrane, using sewage as both the bacteria source and the organic matter and increasing the amount of electrode material. An illustration of these improvements can be found in Figures 8 and 9. Figure 9 shows a photographic image of the completed reactor.

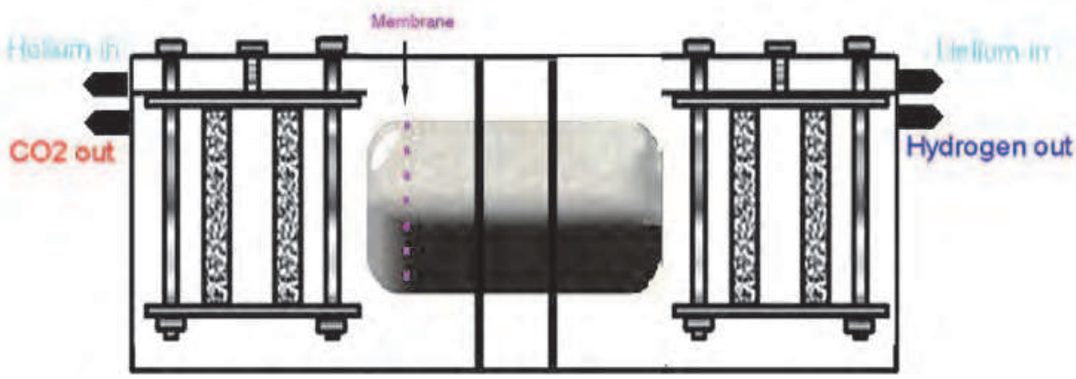

Fig. 8. Two dimensional diagram of the improved cell

Fig. 9. Photograph of improved cell

As shown in Figures 8 and 9, the single electrodes which were held in place by copper clamps have been replaced by double electrodes held by a stainless steel frame. This adjustment was made for two reasons. Firstly the increased surface area of anode and cathode material will allow for more bacterial growth and more reactions occurring in the cathode chamber. Secondly the copper clamps used previously were highly susceptible to rust causing them to need to be replaced frequently and the chamber contents to be contaminated by rust particles. Due to the constant immersion of the electrodes in water stainless steel was the only viable option to use to hold the electrodes in place and resist corrosion.

The Entrant membrane has been replaced with an anion exchange membrane designed especially for such applications. The new membrane may provide better facilitation for protons than the previous material used. Due to the small amount required a free sample was able to be obtained however larger quantities can be exceedingly expensive. Initially bacteria were sourced from river water which should provide an adequate array of bacteria including many exo-electrogens. However as wastewater is more nutrient rich it was thought that it may also be more bacteria rich. The experiment was carried out in the same manner as the previous trial with the same buffer solution used in the anode and cathode chambers.

4.2.2 Results and discussions

The improved cell was operated over a period of 55 days, almost three times longer than the original cell. At the instant of adding the potassium permanganate the cell produced only 0.4mV as compared with the 1.7mV seen in the previous cell. The initial sharp increase in voltage over the first few hours that was demonstrated by the first cell was not seen in the improved cell. The voltage instead was stagnant around the 0.4mV mark for some time.

The recorded voltages and calculated current densities are shown below in Figures 10 and 11 respectively. The maximum cell voltage observed was 4.73mV which occurred 17 days after start time. The corresponding current density is 66.75mA/m^2 with power normalised by anode surface area of .316mW/m^2 and volumetric power 1.36mW/ m^3.

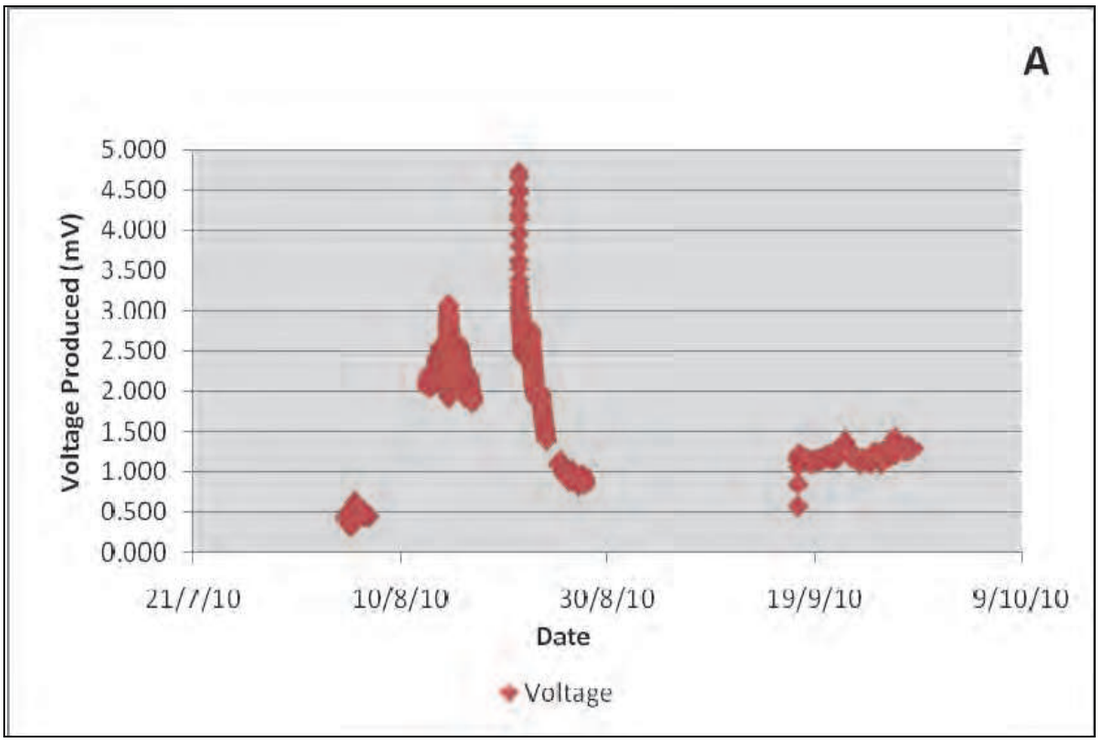

Fig. 10. Recorded voltages from start time (4/8/10) to end time (28/9/10)

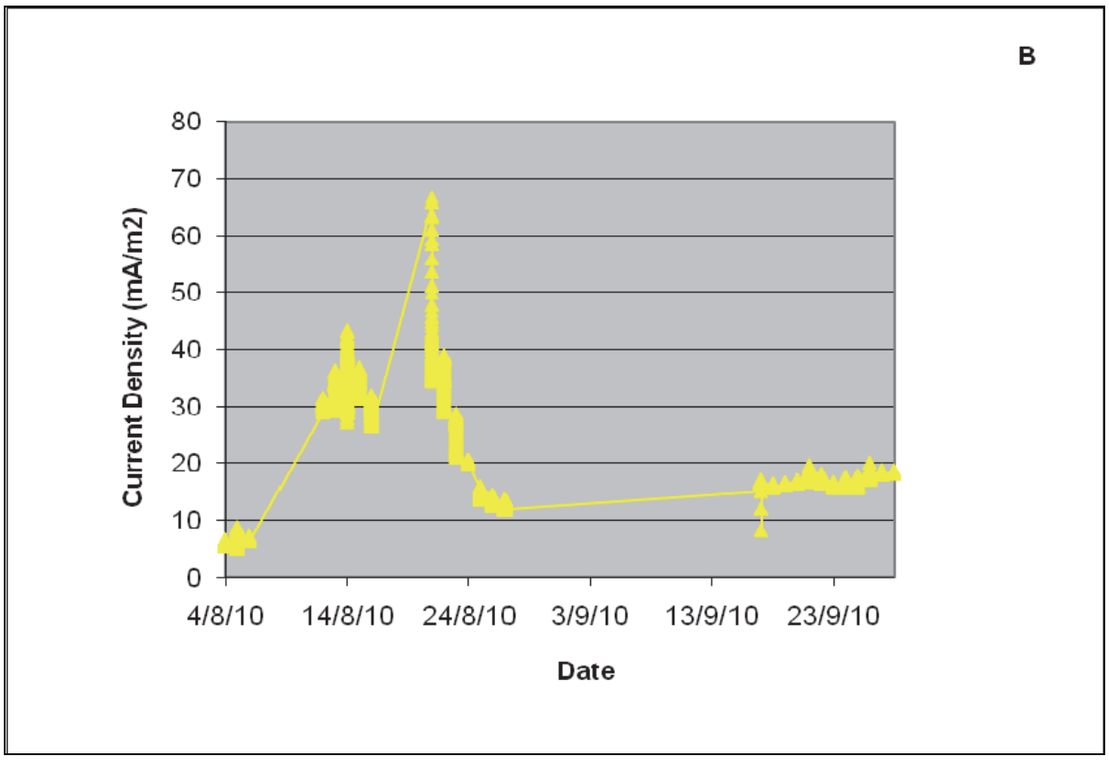

Fig. 11. Calculated current densities over the same period

Rather than improving the performance of the fuel cell, the adjustments made hampered the performance. Time did not permit for a lengthy investigation into the reasons for this however several conclusions can be theorised. It can be concluded that the addition of the stainless steel frame housing the electrodes considerably increased the internal resistance of the cell. This can be deduced by comparing the resistivity of the formerly used copper and the stainless steel which replaced it. The Physics Hypertext book gives copper and stainless steel resistivity of 17.1 (nΩm) and 720 (nΩm) respectively (Alert, 2010). The stainless steel design therefore increased the resistivity the electron travels through by over 40 times that in the original design. This effect was unavoidable as stainless steel was the only metal capable of withstanding the fuel cell conditions without suffering from corrosion. This increased internal resistance would explain a drop in current density as seen in the results.

As discussed previously bacteria growth is extremely important to the voltage produced. It is well known that bacteria favour warm conditions for growth (Answers.com, 2010) . Due to the use of human effluent in the improved cell, health regulations required that it be located in an isolated location. The only available areas were either outside or in a poorly ventilated, cold room. As it was winter at the time of the trial the cell was most often kept at a temperature of around 15 degrees Celsius. The earlier trial however was conducted during summer where the cell was kept at a more suitable 25 – 30 degrees Celsius. These inadequate conditions may have hampered the bacterial growth and decreased the output voltage as a result. The higher temperature may have also contributed to the higher voltage in the cathode chamber. Since heat is a catalyst a higher temperature may have speeded up the reaction in the cathode chamber by causing the protons to have a greater kinetic energy and collide with a higher number of electrons. The heat related effects were demonstrated in the previous trial where the temperature and voltage were recorded and compared over a period of time.

5. Conclusions, outlook and future study

The study presented in this chapter has mainly provided a review of the concept of microbial conversion of biomass into usable energy. An overview of Microbial Fuel Cells (MFCs) has been given, and their significance has been outlined. MFC and MEC systems are recognised as energy production systems with great potentials. The world's need for electricity and fuel is ever increasing and so is the need for clean, renewable methods to produce these things. Microbial cells have the advantage of running off widely available sources of energy including waste water and food scraps. These are things produced by every home around the globe including remote areas and in developing countries.

The study also discussed the design and construction details of two MFCs and presented the results of tests carried out with the constructed cells. The results demonstrate that further work is needed before MFCs could become a commercial success. Reducing the expenses of building and operating an MFC/MEC system as well as increasing cell efficiencies are ongoing issues for the technology. Further research is also required in many areas particularly in the area of catalysts as the cathode with the inclusion of the catalyst has been found to account for almost fifty percent of the cost of an MFC/MEC (Call et al., 2009). Future studies should focus on the incorporation of bacteria on the cathode to replace the current techniques.

Optimal methods for producing a biocathode have not been thoroughly investigated (Logan et al., 2008) however it has been shown that an effective way to produce a biocathode is to reverse the polarity of an MEC (Rozendal et al., 2008; Jeremiasse et al., 2009).
Membrane's also increase the expense of a system so architectures which do not require a membrane are obviously more desirable although they too have their drawbacks. Membrane fabric offers an inexpensive alternative to cation and anion exchange membranes but further investigation as to their comparative performance must be undertaken. Nevertheless MFC and MEC technology is relatively new but advancements to the technology have been rapid and should continue at this pace resulting in higher efficiencies, lower costs and a scalable reactor design in the not too distant future.

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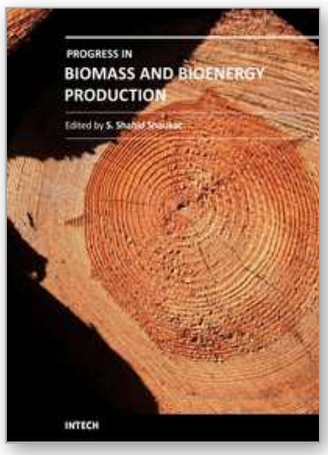

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Alternative energy sources have become a hot topic in recent years. The supply of fossil fuel, which provides about 95 percent of total energy demand today, will eventually run out in a few decades. By contrast, biomass and biofuel have the potential to become one of the major global primary energy source along with other alternate energy sources in the years to come. A wide variety of biomass conversion options with different performance characteristics exists. The goal of this book is to provide the readers with current state of art about biomass and bioenergy production and some other environmental technologies such as Wastewater treatment, Biosorption and Bio-economics. Organized around providing recent methodology, current state of modelling and techniques of parameter estimation in gasification process are presented at length. As such, this volume can be used by undergraduate and graduate students as a reference book and by the researchers and environmental engineers for reviewing the current state of knowledge on biomass and bioenergy production, biosorption and wastewater treatment.

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