

Development of a Phosphoric Acid Fuel Cell for use as Standby Power Supply for Telecommunications Purposes

Thapelo Pholo and Christo Pienaar*

Department of Applied Electronics and Electronic Communication
Vaal University of Technology, Andries Potgieter Blvd., Vanderbijlpark, 1900
Telephone Number: (016) 950-9074 voip 7701#,Email:20214146pholo@vut.ac.za

Abstract - The development of fuel cell (FC) technology offers a novel platform for independence of telecommunication utilities from the national grid, especially for remote repeater stations that are not easily accessible for power connection. Currently, there is a huge interest in the possibility that FCs could make an important contribution to the world energy supplies for both mobile and stationery applications. This paper describes the design considerations of the single cell Phosphoric Acid Fuel Cell (PAFC). The method used for assembly, operation and experimental results together with simulated results of the mono-cell are presented. Details are given only to the experimental and simulated results and not to the design of components. Firstly the assembly is discussed followed by the operational characteristics and the results. Based on the experimental data, the characteristics are then used to simulate the bigger 100 W fuel cell that can be integrated as a backup power supply for telecommunications purposes.

Index Terms- Phosphoric Acid Fuel Cell (PAFC), Fuel cell (FC).

I. INTRODUCTION

In today's society there is an enormous demand for energy. In addition, the electric utility is struggling to meet with the expanding power demands. For these reasons, the application of fuel cell technologies may be one of the most important technological advancements of the next decade.

Although fuel cells would appear to be a new technology, the idea that reversing the electrolysis process should be possible by reacting hydrogen and oxygen to generate electricity was first recognised by Sir William Grove in 1839 [1].

Phosphoric acid fuel cells currently represent one of the fuel cell (FC) technologies that have been demonstrated in many countries around the world and for many applications.

FCs are electrochemical devices that convert the chemical energy of a gaseous fuel directly into electricity and are widely regarded as a potential alternative to stationery and mobile power sources.

* Corresponding authors. Thapelo Pholo is a MTech student at the Telkom center of excellence at the Vaal University of Technology, Vanderbijlpark, South Africa (Email:20214146pholo@vut.ac.za)

Prof Christo Pienaar is the Head of the Telkom Center of Excellence at the Vaal University of Technology, Vanderbijlpark, Gauteng, South Africa. (Email:christop@vut.ac.za)

They complement heat engines and reduce the ubiquitous dependence on fossil fuels and thus have significant environmental implications [2].

Electrochemical energy conversion is defined as a spontaneous reaction in an electrochemical reactor that consumes a fuel and an oxidant and their reactions at the anode and cathode generate electricity, heat and water.

The direct conversion of chemical energy into thermal and electrical energy is facilitated by the electrode-electrolyte structure of the FC. One of the two electrodes (either anode or cathode), will produce the appropriate ions needed to pass through the electrolyte. These ions which can be thought of as free moving are either positive or negative and are then attracted to the opposite electrode through the electrolyte to complete the process.

This paper is organised as follows. Section II provides the operation of the PAFC together with the associated formulae and figures. Section III is the overview of the entire assembly of components. Section IV illustrates the experimental and simulated results obtained by using a MATLAB toolbox. Concluding remarks are drawn in section V.

II. PAFC PRINCIPLE OF OPERATION

A PAFC is composed of two porous gas diffusion electrodes, a cathode, an anode and an electrolyte together with an external load. The anode provides an interface between the fuel (hydrogen) and the electrolyte (Phosphoric acid), catalyses the reaction and provides a path for free electrons. The cathode provides an interface between the oxidant (air) and the electrolyte, catalyses the oxygen reaction and also provides a path for returning electrons from the load to the oxygen electrode via the external circuit. The electrolyte acts as a separator between the fuel and oxidant and also completes the electrical circuit of transporting ions between the electrodes.

The fuel and oxidant (Hydrogen and Oxygen) are fed to the anode and cathode, respectively. The hydrogen and oxygen gases do not directly mix and combustion does not occur. At the anode, hydrogen ionizes to H^+ ions and migrates towards the cathode to combine with oxygen, forming water. The PAFC operates at temperatures ranging from 150-200°C. The reactions at the anode and cathode are as follows [3].

At the anode:



At the cathode:



Overall reaction:



The voltage produced from one cell is between 0 and 1 volt depending on fuel cell operating conditions and the size of the load connected to the FC. Typical value of the PAFC is about 0.7 volts. To get a higher value, multiple cells are stacked in series and hence the total stack voltage becomes the product of the number of cells and the average cell voltage. However, there are some electrical resistances in the fuel cell like in any other electrical device. The loss associated with this resistance is dissipated in the form of heat, which will be discussed in section IV.

FCs have several advantages over internal combustion engines (ICE). ICE converts fuel energy to thermal energy at high temperatures before generating mechanical energy. The efficiency of conversion is therefore limited by the Carnot cycle because of the thermal energy involvement. Unlike ICE, FCs directly converts fuel energy to electrical energy and hence they are not subjected to the Carnot cycle limitations.

The performance and typical characteristics of a FC is normally given in the form of a polarization curve. This is a plot of cell voltage against cell current density (current per unit cell active area). As more current is drawn from the cell, the voltage decreases due to the FCs electrical resistance, inefficient reactant gas transport and low reaction rate. This is shown in Figure 1 below.

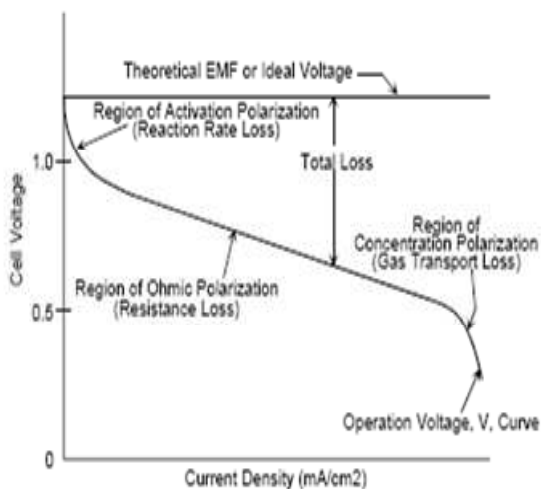


Figure 1. Polarization curve of a FC [3]

III. OVERVIEW OF ASSEMBLY

The primary components of a PAFC are an ion conducting electrolyte (Phosphoric acid), a cathode, and an anode, as shown in Figure 2. The three are together often referred to as a single-cell fuel cell. The electrolyte prevents the direct chemical combustion by separating the fuel (H_2) from the oxidant (air). It also serves as the barrier to gas diffusion, but will let ions migrate across it. The following sub-sections will

discuss different components.

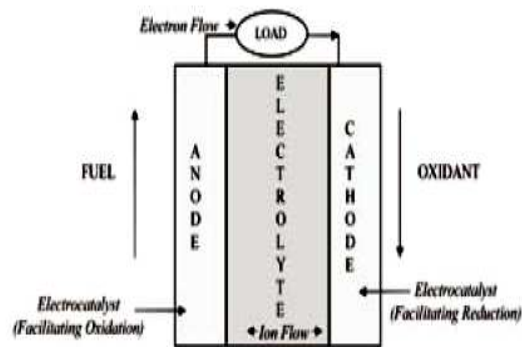


Figure 2. Components of a FC.

A. Electrodes and Gas Diffusion Electrodes

Electrodes for PAFC are generally porous gas diffusion electrodes to ensure the supply of the reactant gases to the active zones where the noble metal catalyst is in contact with the ionic and electronic conductor. The fabrication of gas diffusion electrodes (GDE) is an intricate procedure in which all details of the structure and preparation are important.

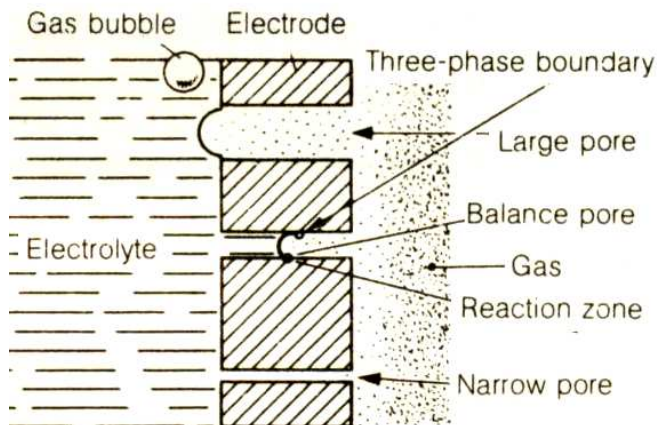


Figure 3. Porous Electrode [4].

The reason for this is that the function of the electrodes is far more than just catalyzing a reaction, which is carried out by the catalyst particles. The preferred catalyst is platinum on carbon. Carbon is bonded with polytetrafluoroethylene (PTFE) to create the catalyst structure. Graphite is the widely used material for cellblocks because of its resistance to corrosion and low electrical resistance. Flow field channels are machined into the graphite blocks to distribute the reactant gases evenly over the entire membrane surface. Column flow pattern is used in this case. The width of 1 mm and a depth of 0.8 mm were chosen for the channels.

B. Electrolyte

The electrolyte permits only the appropriate ions to pass (positive or negative ions). This is why it is mostly referred to as a proton conductor. Phosphoric acid (H_3PO_4) is used as the electrolyte because it is the only inorganic acid that exhibits

the required thermal stability, chemical and electrochemical stability and low enough volatility to be effectively used [5].

Phosphoric acid does not react with CO_2 to form carbonate ions such as the case with alkaline fuel cells; therefore carbonate formation is not a problem with phosphoric acid fuel cells.

Note: electrolyte does not react with the ions.

The H_3PO_4 is uniquely contained in a silicon carbide particle matrix using capillary action. The silicon carbide matrix which holds the electrolyte is produced with particles approximately 1 micron in size allowing the matrix to be about 0.1-0.2 mm thick [5]. This thickness allows considerably low ohmic losses. The structural matrix is thick enough to prevent cross over of the reactant gases from the anode to the cathode.

C. Gaskets

The gaskets are made of an incompressible PTFE material with a thickness of 0.25 mm and can withstand the high operational temperatures of up to 200°C. This ensures that they cannot shrink due to high temperatures and therefore leak the reactant gases.

D. Assembly

The fuel cell developed during this study was a single cell with an active electrode surface area of 25 cm². The FC can produce 4-7 W continuous power at less than 200 mA/cm². It was also designed to operate at temperatures from 150-200 °C and low gauge pressures (<15 KPa) for both anode and cathode. The dimensions of the fuel cell were 110 x 110 mm. Phosphoric acid matrix assemblies were designed to provide consistent and reproducible performance. Wet-proofed carbon paper was used as a support for 10 wt. % Pt/C based electrodes. High purity silicon carbide (SiC) was used as the matrix.

The FC was assembled using PTFE sheets as gaskets and a torque of 5 Nm was used to tighten the bolts. The choice of the torque was based on previous work and experiments. Small FCs can be operated without humidifiers and hence they were not used. This means that the reactant gases were not humidified.

The temperature of the cell was controlled with a temperature controller with two thermocouples inserted into the thermocouple wells on the sides of the graphite plates. The resistive heaters and the controller kept the temperature at 150 °C during operation and measurements. The reactants flow rates were controlled using the mass flow controllers.

The SiC membrane soaked with H_3SO_4 was firstly placed on top of the anode with gasket facing the acid reservoir. The concentration of H_3SO_4 can be between 85 to 100%, with 100% producing better performance. Acid concentration of 89% was used. The second membrane also soaked in acid was then placed on top of the face gasket and covered with the cathode gasket and graphite plate. At both ends of the electrode blocks, stainless steel endplates were used to ensure adequate and uniform contact pressure with heaters attached onto them for heating the FC. The entire assembly is compressed together with eight bolts at a torque of 5 N.m. The FC is assembled as shown in Figure 3 below.

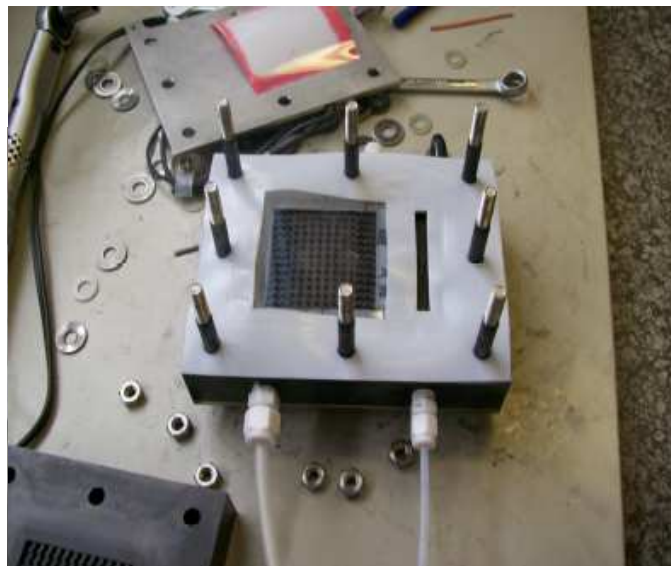


Figure 3. Fuel cell being assembled

IV. EXPERIMENTAL

A common safety concern for the FC systems is hydrogen leaks. As hydrogen is a combustible material and its uncontrolled release can carry risks. Hydrogen has the lowest molecular weight and viscosity of any gas. Due to its properties it has a faster leak rate through small orifices than any other gas. It is difficult to contain Hydrogen gas as it escapes easily.

In pure hydrogen fuel cell stacks there is always an accepted leak level as it is impossible to completely seal the cells. An increase in leak due to rupture of seals can be the cause of a critical concentration of hydrogen to form which in turn can lead to an explosion.

An air test approach was used to address this problem. The main requirement for the leakage detection is swift and reliable detection along with simplicity. Pressure sensitive paper films were placed between the gaskets in order to ascertain the exact points of leakage. It was important that a uniform contact pressure existed between the gaskets. This film contained microcapsules filled with ink. As more pressure was applied to the film, more of these capsules broke open and released their ink resulting in darker colored areas of more pressure. The color variation helped in resembling places where reactant gases were leaking and in bolt torque control.

The FC was assembled using various torques until settling for 5 N.m. The FC was reassembled with another pressure paper film with an increased torque. This yielded positive results. Even though the paper film showed that there was no leak this time, the torque was too much for the membrane to handle. The chosen torque had to yield sufficient gas tightness while minimizing the diffusion overpotentials due to the compression of the gas diffusion layer.

A. Results and simulations

Electrical energy is obtained from a FC only when a current is drawn, but at the same time, the cell voltage drops due to various irreversibilities (losses). In practice, the terminal voltage is generally lower than the calculated electromotive

force (EMF) due to the three major polarizations. The voltage-current curve of a FC as shown in Figure 1 is also referred to as a polarization curve. The polarizations are: 1) activation polarization ΔV_{act} ; 2) concentration polarization ΔV_{conc} ; and 3) ohmic polarization ΔV_{ohm} [3].

Activation polarization is caused by the three-phase interface and by the loss of voltage due to activation energy that drives the chemical reactions for electron transfer. It can be expressed in many ways and the simple form is:

$$\Delta V_{act} = A \ln(i/i_0) \quad (4)$$

Where:

- $I \equiv$ the local current density in mA.cm^{-2}
- $A \equiv$ a constant and it is higher for an electrochemical reaction that is slow
- $i_0 \equiv$ the current density, which is the current at which the voltage drop moves away from zero. It is usually called the exchange current density in mA.cm^{-2}

The ohmic polarizations occur due to resistance to the flow of ions in the electrolyte, resistance to the flow of electrons through the electrodes and the contact resistance at the cell terminals. As shown on the curve, it is fairly linear. This voltage drop is proportional to the current density i and is modeled by:

$$\Delta V_{ohm} = ir \quad (5)$$

Where:

- $r \equiv$ an area specific resistance (ASR) in terms of $\text{K}\Omega.\text{cm}^2$.
- $i \equiv$ exchange current density in mA.cm^{-2}

Concentration polarization arises due to a decrease in concentration of the reactants at the interface. The differences causes the concentration polarizations, which are therefore, more pronounced at the high current densities as shown in Figure 1. A steady supply of the reactants is required at the electrode-electrolyte interface to maintain the flow of electric current. Due to diffusion or convection problems in the electrolyte, the concentration of the reactants is not maintained at the initial level. The concentration gradient thus formed, causes a drop in electrolyte activity and the terminal voltage is reduced. The concentration polarization is modeled by:

$$\Delta V_{conc} = me^{ni} \quad (6)$$

Where:

- $m \equiv$ a constant in terms of $\text{V cm}^2.\text{mA}^{-1}$
- $n \equiv$ a constant in terms of $\text{V cm}^2.\text{mA}^{-1}$

The output voltage of a FC is obtained by adding all the above losses (activation, ohmic and concentration), and

subtracted from the Nernst Equation, which is the reversible open circuit voltage.

$$V = E + A \ln(i_0) - ir - A \ln(i) - me^{ni} \quad (7)$$

In the following equation, the first two constants are replaced by E_{oc} and this yields:

$$V = E_{oc} - ir - A \ln(i) - me^{ni} \quad (8)$$

Where:

$E_{oc} \equiv$ open circuit voltage

Equations (4)-(8) were used to model the characteristics of a PAFC using Matlab Toolbox. The model represents the performance behavior at a range of current densities.

TABLE 1
SINGLE CELL PERFORMANCE DATA

| Stack voltage (V) | Current (mA.cm^{-2}) | Current (A) |
|-------------------|---------------------------------|-------------|
| 0.8 | 24 | 0.6 |
| 0.74 | 28 | 0.7 |
| 0.73 | 32 | 0.8 |
| 0.71 | 34 | 0.85 |
| 0.7 | 36 | 0.9 |
| 0.68 | 38 | 0.95 |
| 0.67 | 39.6 | 0.99 |
| 0.66 | 40 | 1.0 |
| 0.65 | 42 | 1.05 |
| 0.63 | 44 | 1.1 |
| 0.59 | 46 | 1.15 |
| 0.55 | 48 | 1.2 |
| 0.51 | 64 | 1.6 |

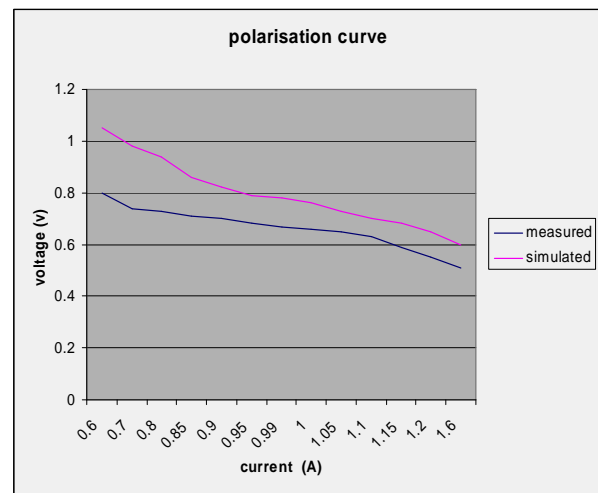


Figure 5. V-I curve for simulated and measured data

The shape of these curves of the output voltage is non-linear as activation loss occurs at low current densities and mass

transport loss at high current densities. Ohmic polarization affects the fuel cell output voltage in the middle of current densities and produces a linear relationship between voltage and current density.

The graph in Figure 5 shows the polarization (V-I) curves of the developed single cell from the experimental data (Table 1) and its corresponding simulation. It is evident from the graph that the shape of both curves is almost the same; however, there is a consistent voltage difference between them. This is due in part to the difference in standard conditions in practice and the simulation conditions. The simulation current exchange density could not be matched due to fluctuations in the flow rate and impurities in the membrane also affected the output voltage.

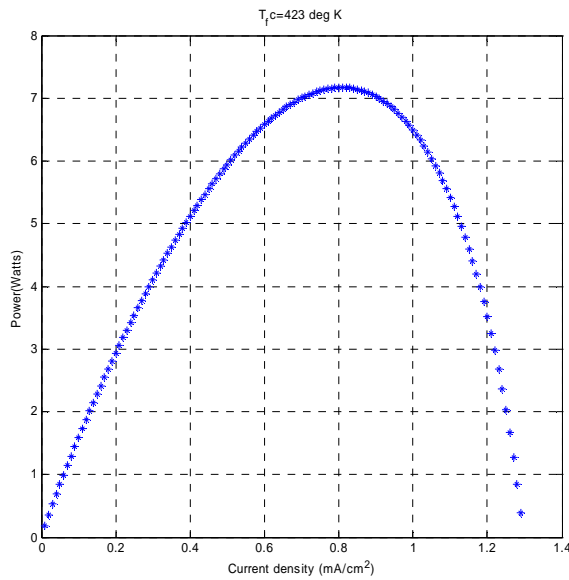


Figure 6. Power-current density graph (simulated)

The output power is given by the following equation:

$$P_{FC} = V_{FC} I A n \quad (9)$$

Where:

- $n \equiv$ Number of the fuel cell stack
- $A \equiv$ Area of stack cm^2
- $I \equiv$ Current Density A/cm^2

Typical PAFC operate around between 0.6 and 0.7 V per cell, in order to maintain a balance between system power and efficiency losses. There is always a desire to operate at higher voltages, because of increased efficiency and reduced flow requirements. However, the output power typically peaks around 0.6 to 0.7 V, so there is a size tradeoff for voltage operation. The output power of the FC can however be increased by decreasing the temperature of the FC but losses discussed in IV are nearly always less at higher temperatures.

B. A 100 W FC model

The experimental performance data derived from a single cell

can now be extrapolated to formulate an economical and efficient 100 W PAFC model.

The experimentally determined power for one cell was around 1-2 W, which, if a linear extrapolation is assumed, implies that the number of cells required for a 100 W system is:

$$\begin{aligned} \text{Cells required} &= \text{system power}/\text{cell power} & (10) \\ &= 100/2 \\ &= 50 \text{ cells} \end{aligned}$$

The FC operates well below the nominal operating voltage at power densities depicted by the fairly linear response on the curve shown in Figure 1. The lower the output voltage means the overall efficiency of the system is reduced, therefore the system must be modeled at parameters resulting in maximum efficiency.

The maximum power capability of a single cell is in the order of 4 W. The number of cells capable of supplying the application with the required power can then be calculated as follows:

$$\begin{aligned} \text{Cells required} &= 100/4 \\ &= 25 \text{ cells} \end{aligned}$$

The stack voltage can now be calculated using the following equation:

$$\text{Stack Voltage} = N_{\text{Cells}} \times \text{Cell potential} \quad (11)$$

Where:

$$N_{\text{Cells}} \equiv \text{Number of cells}$$

Although the 25 cells will be capable of supplying the 100 W, it does not take into account the current drain during normal operation and fuel usage efficiency. For maximum fuel utilization, the current drain must not exceed 2 A per cell (0.9 V). The maximum power load per cell can now be calculated using the following equation:

$$\begin{aligned} \text{Maximum Power}_{\text{cell}} &= \text{cell voltage} \times 2 & (12) \\ &= 0.9 \times 2 \\ &= 1.8 \text{ W} \end{aligned}$$

Thus, for a stack that will operate at maximum efficiency, the number of cells needed can be calculated at a maximum power load per cell of 1.8 W, as follows:

$$\begin{aligned} \text{Cells Required} &= 100/1.8 \\ &= 56 \text{ Rounded} \end{aligned}$$

The total energy required to power a 100 W telecommunication system for at least one month can be calculated as follows:

$$\begin{aligned} \text{Energy} &= 100 \text{ W} \times 24 \text{ h} \times 30 \text{ days} & (13) \\ &= 72000 \text{ Wh} \end{aligned}$$

V. CONCLUSION

The performance characteristics of a single PAFC under varying conditions were explored. The modeling parameters were acquired to model a 100 W PAFC stack that could be used in telecommunication systems. The various losses were also discussed and used to model the characteristics of the FC.

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