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Design and Implementation of Hydrogen Fuel Cell as a Means of Alternative Energy

Iyere Sunday Fidelis[1, *], Idim Aniebiet Idim[2]

[1]Department of Electrical and Electronic Engineering, Faculty of Engineering and Technology, Ambrose Alli University, Ekpoma, Nigeria
[2]Department of Electrical and Electronic Engineering, Petroleum Training Institute, Effurun-Warri, Nigeria

Email address:

sunday4success2007@gmail.com (I. S. Fidelis), sunday4success@aauekpoma.edu.ng (I. S. Fidelis), aniebietiidim@gmail.com (I. A.Idim)
[*]Corresponding author

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Abstract: The demand for electrical energy is on the increase particularly in a developing economy such as Nigeria, where the government has not been able to provide adequate and uninterruptible power supply to her fast growing population. More research is needed to bring electricityto the door step of the people by diverting attention into other sourcesof energy which can stand as viable alternative to the conventional sources of energy. This research is aimed at employing the potentials of water electrolysisto produce hydrogen fuel cell which can be used to power electrical appliances, among other applications. Step-by-step procedures where observed in using locally available materials to construct a containment of hydrogen fuel cell with an electrolyte and two electrodes separated apart into two equal halves of a transparent box made of Perspex. A light bulb (resistive load) was connected across the output terminals, and voltage/current variation s with respect to time was measured using appropriate instruments in order to deduce charging, discharging power and efficiency of the fuel cell. Graphs of measured values were plotted to determine their characteristics including the current/voltage (I-V) characteristics curve of the hydrogen fuel cell. Results of measured values and characteristic curves show that hydrogen fuel cell capable of powering electricalloads was produced, and the current density is dependent on the surface area surrounding the electrodes. That is, the wider the surface area around electrodes the higher the electrical energy generated.

Keywords: Electrolyte, Electrode, Hydrogen, Gas, Fuel, Cell, Electrical Power

1. Introduction

1.1. Background

Fuels are prominent source of energy which when burned in the presence of oxygen release energy for productive or comfort use. Conventional fuels, which include wood, coal, oil, and natural gas, are made up of organic compounds of mainly carbon and hydrogen. During combustion or burning, both carbon and hydrogen combine with oxygen, to release thermal energy. The byproducts of the combustion ofcarbon are carbon dioxide and carbon monoxide which are respectively greenhouse gases (GHG) that pollutes the environment. But the byproduct of hydrogen when it reacts with oxygen is water which is less harmful with no environmental pollution and atmospheric heat. And so, therefore, the lowerthe carbon content in the fuel being exhausted, the cleaner and healthier it is for the environment and mankind [8, 17]. This is the rationale bordering the concept of decarbonization. Decarbonization is the process of reducing the relative amount of carbon in fuels to ensure cleaner combustion. The concept has been of very keen interest across the world in recent times due to the effect of global warming caused by fossil fuel discharge, as it affect the climatic and weather condition of the various countries the world over. There is an increased concern for clean energy, resulting in diversion from wood, coal, oil to natural gas which contains methane as the main constituent. Forevery atom of hydrogen, the fuels; wood, coal, oil and natural gas contain about 10, 1.5, 0.5 and 0.25 of atoms of carbon, in an increasing order of cleanliness. This implies that,. Natural gas is the cleanest amongst the non-carbon free fuels because it releases the least number of carbon per unit of energy produced. For fuels to be absolutely clean, carbon has to be totally removed

[12, 13, 17]. Thedecarbonization result to the use of pure hydrogen as a source of fuel. Hydrogen being the most abundant element on earth does not exist in its free state (H_2), but it is found in organic molecules such as hydrocarbons. Thus hydrogen production is a huge investment because it is used mostly in the production of the nitrogen-based fertilizers and cracking of petroleum. However, fuel and energy storage are the potentially most significant future application of hydrogen [5, 7]. That is, hydrogen is used in fuel cells which convert chemical energy directly into electrical energy with high efficiency Ball and [7, 8, 13, 18]: they have been projected to double the efficiency of the current internal combustion engines. The electric efficiency typically falls within the range of 40 to 60% for gaseous or liquid fuels; about 30-40% of the energy of the fuel is available as heat. In fuel cells, hydrogen reacts with oxygen to generate electricity (as the main product) and heat and water (as by-products). The released energy in equation (1) is a combination of electrical energy and heat. The two byproducts can be used for other purposesvarious. The produced heat can be can be used for pre-heating purposes and the pure water can be used wherever clean water is needed like cleansing and drinking [7, 13, 15].. Fuel cells are efficient, durable (because they do not have moving parts), easy to operate/maintain and noiseless., [11, 12] "Water electrolysis has been used industrially to produce hydrogen for more than a century due its efficiency and capacity for increased production and energy drive [9, 16, 21].

1.2. Significance of Hydrogen Fuel Cells

As the quest for alternative and clean energy increases around the world, hydrogen fuel cells are reliable alternatives to the conventional system of electrical power generation methods in small-scale applications because hydrogen fuel contains significant chemical energy. In terms of energy storage capacity, hydrogen fuel cell is better than the conventional battery as it does not require charging for it to maintain its electrical energy. Hence it is fast becoming widely developed for other numerous energy applications [11]. According to Afif, et al [6], hydrogen and fuel cells are considered the key components of energy solutions for the 21st century energy production. This conclusion was reached based on the significant potential benefits fuel cell technology offers in reducing environmental impact, enhancing energy security (and diversity) and creating new energy industries. Various industrial opportunities have emerged, including; transportation, distributed heat/ power generation and energy storage systems industries [6, 8, 11]

2. Literature Review

2.1. Review of Some Previous Researches

2.1.1. Waste Water Biorefinery Based on the Microbial Electrolysis Cell; Opportunities and Challenges

In this research, Waqas, et al, [1] present a novel method of producing hydrogen in a process known as electrohydrogenesis, which is done by carefully selecting various parameters such as electrode sizes, area of system membrane, quantity of gas collection and type of tubing as well [1]. There are different designs of Microbial Electrolysis Cell (MEC) which include single-chambered and double-chambered MEC systems for hydrogen production. The systems are facing the problem of over potential resistance and ohmic losses, methanogenesis (conversion of water to methane), high cost of reactor design and the nature of the electrode material. The report however explained that when chemical or biological cathodes are used, over potential and high internal resistance will be minimized by exposing the anode biofilms and analyte in MEC systems so that methanogens can be inhibited and selecting biochemically active microbes with high electroactivity and efficiency of electrons will yield better output [1, 3]. The research however involves the use of materials which are not within reach in a developing society like Nigeria in, addition to the problem ofohmic losses and overpotential resistance associated with MEC process. Apart from the setbacks mentioned above, there is also the problem of methanogenesis where the end product becomes mostly of methane gas instead of hydrogen and others [7, 10, 19].

2.1.2. Fuel Cells: Microsystems Reference Module in Material Science and Materials Engineering

Hyu, [2] took a study of the process that produces hydrogen nucleus made up of protons and electrons in sufficient detail. The report says that the reaction taking place in a Fuel cell is capable of breaking down hydrogen into molecules with good electrical characteristics. The electrons represent electric current which flows from anode to cathode through the electric circuit while the protons migrate from the anode to cathode using the electrolyte as a medium, and then reacts with electrons flowing through the load in combination with oxygen molecules. The combine reaction produces only water as the product of fuel cell [11, 15, 19]. The article states that, platinum was used as electrolyte for the electrochemical reaction, [2] and so, the work may require a lot of capital to undertake which may cause problem of affordability in further research in achieving better results and developmental achievements [7, 8].

2.1.3. Microbial Fuel Cells as a Platform Technology for Sustainable Waste Water Treatment

VereraGnaneswarGude, [3], described that additional benefits were discovered from the MEC system with respect to microbial fuel cell process. The report shows that apart from some benefits like waste water treatment and energy generation, precious metals such as copper, gold, silver and vanadium can be recovered in the process, while problem metals such as chromium, mercury and manganese can be removed with the same principle by adopting cathodic compartment technique. This method requires additional materials to produce cat ions, and this makesit complex and expensive.

2.1.4. Design of an Alkaline Fuel Cell

In this article, Mohammed Alhassan and Mohammed Umar [5] designed an alkaline fuel cell operating at a temperature range of 100-250°C. Hydrogen was liberated at one electrode while oxygen gas was bubbled into the other. And an ammeter connected between the two electrodes indicated current flow from one electrode to the other during test. The report did not state the type of material used for the electrodes, but the heat of enthalpy for hydrogen and oxygen were recorded to be 288.98 kJ/hr and 147.06 kJ/hr respectively. Total power generated by the cell is approximately 121 W with a volume of 303.3/0301 m^3. The by-products of the fuel cell are potassium carbonatewith an enthalpy of -1.11x10^6 kJ/hr and water having an enthalpy of -9.71x10^5 kJ/hr.

2.1.5. Batterial Metabolism – Coupled Energetics

R. S Prakasham and B. Sudheer Kumar, [4] discovered that microbes in their pure or mixed culture state can undergo some electro activity by transferring energy between microbe and its external environment. This results in production of electricity without any effect on the environment with the microbial fuels [1, 4].

2.2. Basic Operational Principle

A fuel cell has four main parts: anode (a fuel electrode), cathode (an oxidant electrode), electrolyte and the external circuit. The electrolyte is usually sandwiched between the electrodes. The simplest conceptualization of the operation of a fuel cell is that at the anode hydrogen is oxidized into protons and electrons while at the cathode oxygen is reduced. Fuel cells generate electricity and heat via electro chemical reaction. Electrochemical reaction is the reversal of the familiar electrolysis reaction. During operation, protons or oxide ions (depending on the electrolyte) are transported through an ion-conducting electron-insulating electrolyte while electrons travel through an external circuit to deliver electric power [2, 11]. The free hydrogen is delivered to the anode as a gas stream where it reacts electrochemically in the presence of a catalyst. The hydrogen is oxidized to produce hydrogen ions and electrons [5]. The equation for this oxidation process is

$$H_2 \rightarrow 2H^+ + 2e^- \quad (1)$$

The protons migrate through the acidic electron-insulating electrolyte while the electrons are forced through an external circuit (load) to the cathode. At the cathode, oxygen supplied from an external gas-flow stream reacts with the electrons and the protonsto form water and energy according to the following equation

$$O_2 + 2H^+ + 2e^- \rightarrow 2H_2O \quad (2)$$

2.3. Review of the Enabling Technologies

Water electrolysis consists of circulating a direct current between two electrodes (anode and cathode) which are immersed in a water-based electrolyte. The circulating current drives the separation of water into hydrogen and oxygen [16, 18, 20]. For an acidic electrolyte, the cathodic and anodic reactions in water electrolysis are respectively

$$2H^+ + 2e^- \rightarrow H_2 \quad (3)$$

$$\text{And } 2H_2O \rightarrow \frac{1}{2}O_2 + 2H^+ + 2e^- \quad (4)$$

while for an alkaline electrolyte, the cathodic and anodic reactions are respectively

$$2H_2O + 2e^- \rightarrow H_2 + 2OH^- \quad (5)$$

$$2OH^- \rightarrow \frac{1}{2}O_2 + H_2O + 2e^- \quad (6)$$

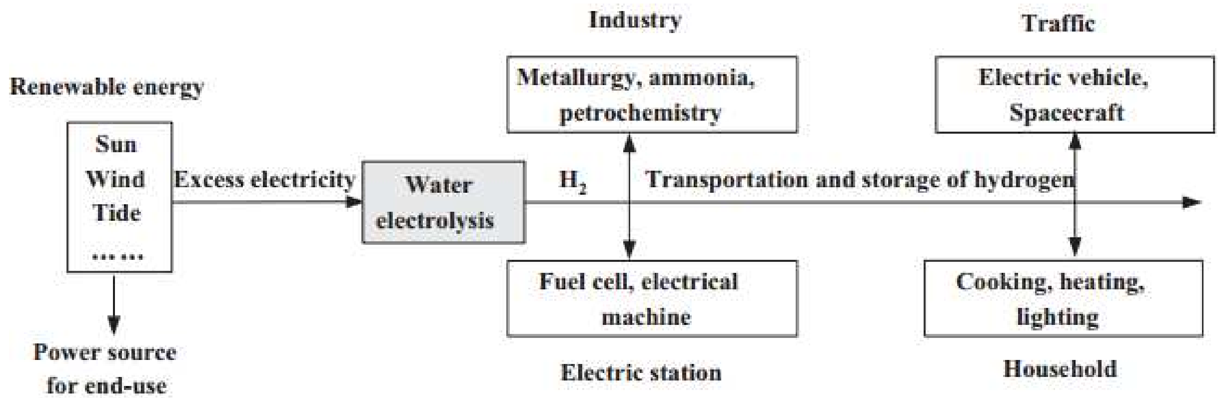

Figure 1. *Sustainable production and application of energy based on renewable energy and water electrolysis* [21].

Recent progress in production of hydrogen using alkaline and acidic water electrolyses have been reviewed [5, 15, 18]. As can be seen from the equations, electrical energy is required to power water electrolysis. In practical water electrolysis, hydrogen gas evolution rate is low and energy consumption rate is high. This is due to the practical efficiency of 61.5% of water electrolyzers [21]. As a result, the use of the electricity deriving rather inefficiently from conventional sources to power water electrolysis for revolutionary application of fuel cells will fail the sustainability criterion. Electricity from renewable energy resources have been recognized as the only viable driver of water electrolysis for long-term exploitation of fuels in the energy intensive applications [14]. Water electrolysis has, therefore, gained major attention as a potential technology to help facilitate the large-scale integration of intermittent renewable energies [8, 14]. The key to achieving such a milestone is illustrated in figure 1. Regions like the EU already have an exemplary policy for water electrolysis [9]. The details of the technology, chemistry and thermodynamics associated with water electrolysis can be found in literature [16, 18, 21].

3. Materials and Methods

Constructionof the hydrogen fuel cell begins with sourcing for the various materials after designing their specifications. Thereafter, the electrolytic fuel cell was constructed and its operation was demonstrated by connecting a lamp across the electrodes and measuring the voltage current with a multimeter with the view to achieving the stated objective. The testing was done by powering a load such as a bulb on the developed fuel cell. The objective behind this is to evaluate the performance of the system using the concept of energy efficiency necessary for assessing the functionality and market feasibility of the unit. The following procedures where observed in carrying out the work.

3.1. Physical Development of the Fuel Cell

Hand tools, machine tools, welding machines, etc will be used to construct the physical structure of the fuel cell like the containment, frame/base, collectors, electrodes etc. The procedures adopted in the physical construction of the fuel cell are as highlighted as follows;

(i) The Perspex is placed on a flat surface and with the aid of a pencil and a metal rule dimensions are marked out on it. For the sides, four (4) different pieces with dimensions 2 by 3.5 inches are marked out. For the outer base and top, two pieces with dimensions 2 by 3 inches are marked as shown in Figure 2. Still on the base and top, four (4) drill points are marked ¼ inches from side ends.

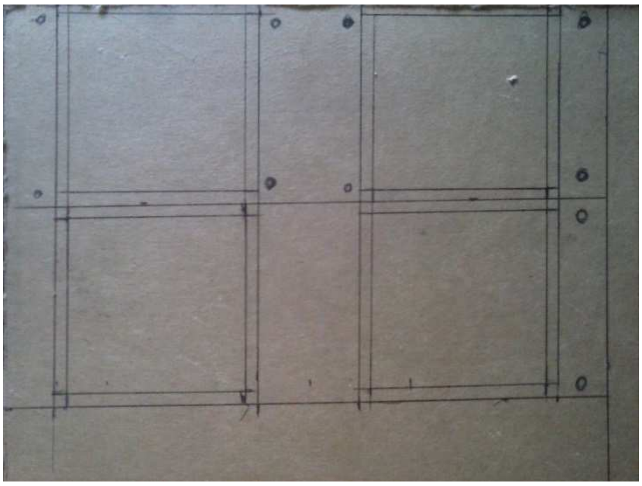

Figure 2. *Marking out of the dimensions of the fuel cell containment on perspex.*

(ii) The top, outer base, inner base, separator and the four sides are then cut out using a cutter. The complete cut Perspex is shown in Figure 3

Figure 3. *Cutting of marked Perspex.*

(iii) The four sides are glued together (using epoxy). The glued sides are shown in Figure 4. Silicon seal is then applied to the end to prevent it from reacting with the NaOH solution that will later be used as the electrolyte.

Figure 4. *Outer case development for the fuel cell.*

(iv) The top and the outer base are placed together to form an edge to edge alignment. Then four holes with diameter 5mm are drilledat point ¼ inches from the edges as marked out in step one.

When the glue (epoxy) holding the four sides are strong enough, the separator is then fixed in place, such that it divides the sides into two equal halves, epoxy is then applied to make it remain solidly in place. The inner base is also put in place to help support the separator.

Note that the inner separator must be placed in such a way that the fluid (gas or liquid) above the inner base cannot mix, but below the inner base the fluid can comfortably mix together. It will be observed that the only way fluid is transferred between chambers is through the base opening, which keeps the hydrogen separate from the oxygen.

Figure 5. *Case and inner separator having silicon seal applied to its corners and joints.*

(v) Since we are using two stainless steel spatulas as the electrode, the spatula is beaten flat and drilled at the rounded end to accommodate the connector bolt. The other squared end is then rolled to reduce the length of the spatula. A brass bolt is attached to the end of each spatula through the hole drilled and fastened in place with a nut.

Two holes, having the same size as the bolt is drilled through the top Perspex centre aligned. The holes should be ¾ inches apart. The electrodes are attached through the centre aligned holes with a washer. It is then covered with silicon sealto prevent escape of fluid.

Figure 6. *Top view of cell showing the electrodes cover and the applied silicon seal.*

(vi) Next, silicon seal is placed on the top and bottom ends of the cuboid to prevent escape of fluid and then the top cover having the electrodes fixed is lowered gently to torch the seal (do not apply pressure). The bottom cover is also sealed in like manner sealing off the cell. For the power pack (for charging the cell), the power rating is of utmost importance. The voltage is important but so is the current since it contributes to the total power input. The charging rate is highly dependent on the surface area of electrode in contact with the water solution. The maximum voltage should however not exceed 80V in other to prevent shock. The output voltage is dependent on the surface area of electrode in contact with the gases (hydrogen and oxygen).

Figure 7. *The constructed hydrogen fuel cell.*

3.2. Experimental Measurements

Multi-meters which have inbuiltvoltmeters and ammeter were used for voltage and current measurements of the developed fuel cell. Digital equipments were preferred for accuracy. Voltage and current are the key inputs to performance evaluation of fuel cells. The adapter supplies direct current of 3.33 A at a known voltage of 19.5 V. So that the energy input to the developed fuel cell canbe known. The resistor of 1 Ω, used as the load, is seen to connect the two red wires in Figure 8.

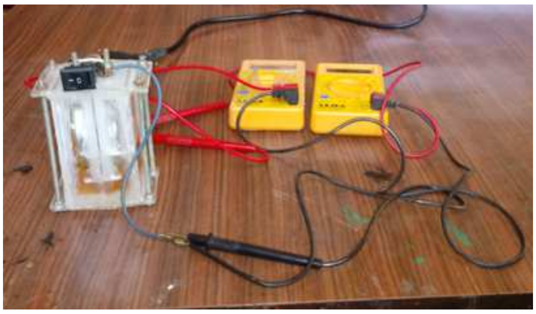

Figure 8. *Experimental setup for Measuring Voltage and Current.*

4. Discussions

The schematic summarizing the parts and the dimensions of the constructed fuel cell is presented in Figure 9. The construction is made to act as an electrolyzer during charging but to revert to a fuel cell during discharging. The dimensions are necessary for the calculation of some performance indices.

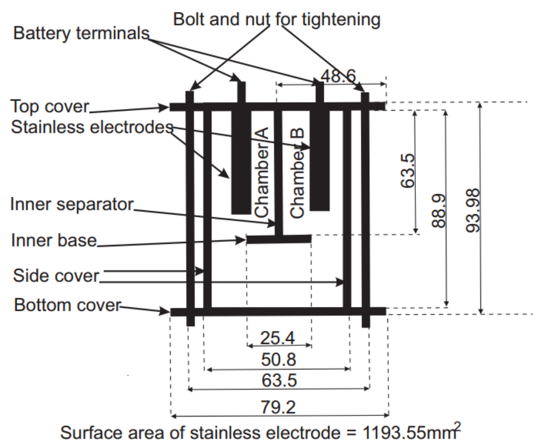

Figure 9. *The constructed fuel cell with annotations and dimensions.*

4.1. The I–VcharacteristicCurves

The data collected from measuring the current and voltage of the constructed fuel cell as setup in Figure 8 are plotted against time in Figures 10 and 11. The measured currents and voltages correspond to the discharging mode of the fuel cell after being charged for one minute. Care was taken to avoid leakage of the electrolyte due to overcharging and consequent pressure buildup. The net cell resistance is roughly constant as expected. It mostly varied between 35 Ω and 45 Ω. The I-V curve is plotted in Figure 12. A smaller range of the I-V curve is plotted in Figure 13 and it seems to align with the expectation that the curve typically varies logarithmically at the low current range and varies linearly at the high current range. Usually, I-V curves are presented in terms of current density to make it possible to compare cells of different surface area. The current density is the cell current per unit area of the cell electrode which in this case is given as

$$J = \frac{1000I}{2A} \quad (7)$$

where, A=1193.55 mm^2 and the division by two is because of the two faces of an electrode. The equation is then used to plot the J-V curves in Figures 13 and 14..

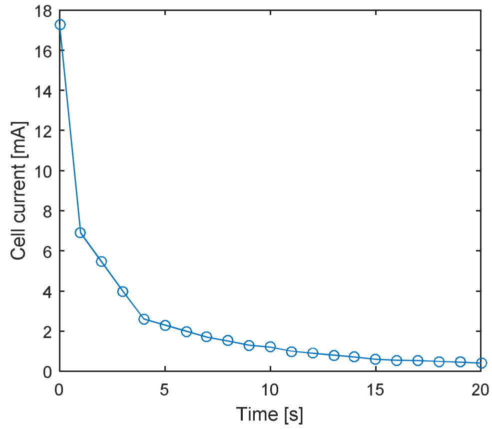

Figure 10. *Variation of cell current with time.*

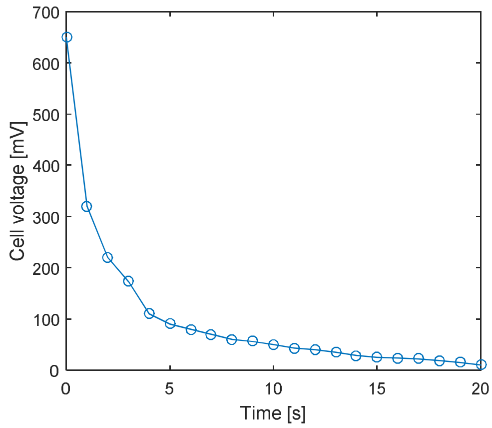

Figure 11. *Variation of cell voltage with time.*

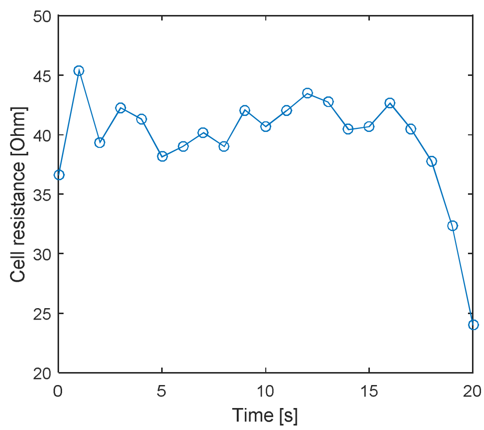

Figure 12. *Variation of net cell resistance with time.*

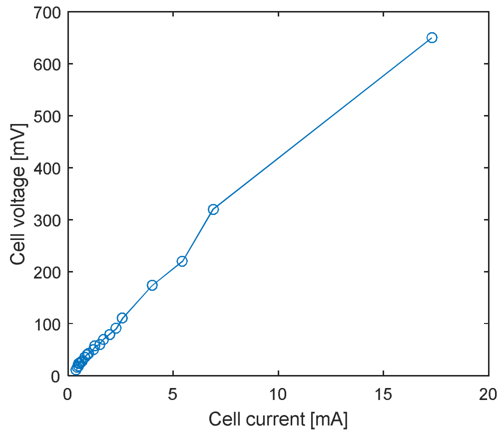

Figure 13. *The I-V characteristic curve for the constructed fuel cell.*

A smaller range of the I-V characteristic curve for the constructed fuel cell showing logarithmic and linear variation at low and high current ranges.

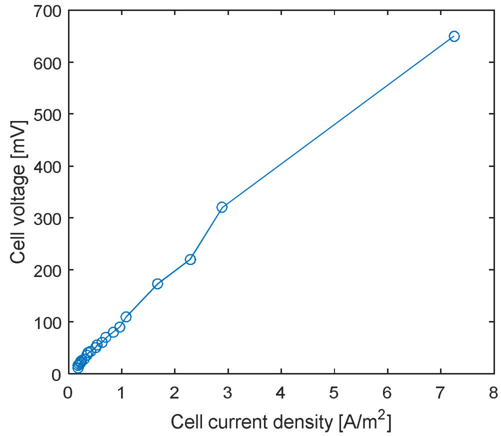

Figure 14. *The J-V characteristic curve for the constructed fuel cell.*

4.2. Hydrogen Production Rate

The fuel cell was charged for one minute with direct current of 3.33A and voltage of 19.5V. In Equation (3.4) for hydrogen production rate (f_{H2}), $N_{cell} = 1$, $I_{cell} = 3.33$A,$z = 2$, $F = 96\,485\frac{C}{mol}$ and adopting $\eta_F = 0.95$ (Ursua et al., 2012).

The hydrogen production rate becomes

$$f_{H2} = 0.95\frac{3.33}{2 \times 96485}\frac{22.41}{1000}3600\text{Nm3/hr}$$
$$= 0.0013\text{Nm3/hr}$$

Therefore, on charging the constructed fuel cell for one hour, the hydrogen production is

$$Q_{H2} = \frac{0.0013}{60} = 2.1667 \times 10^{-5}\text{m}^3 = 21.6670\text{cm}^3$$

Using the I-V data, the hydrogen production rate is estimated at $0.0013\,\text{Nm3/hr}$, the hourly hydrogen production was estimated at 21.6670cm^3 , base on the trapezoidal rule of numerical integration the specific energy consumption was estimated at $2.7491 \times 10^3 J/\text{Nm}^3$ and the efficiency was estimated at 3.0405%. The low value was attributed to irreversible reactions and external resistor attached during discharging of the fuel cell.

4.3. Efficiency

Using the I-V characteristic values of discharging process in the numerator and the I-V characteristic values of charging process in the denominator, efficiency is calculated thus

$$\frac{\sum_i I_i V_i)_{\text{discharging}}}{\sum_i I_i V_i)_{\text{charging}}} 100 = 3.0405\%$$

The low value could be due to external resistor attached during discharging of the fuel cell.

5. Conclusions

A detailed procedural approach has been presented in developing hydrogen fuel cell in this work, and the fuel cell produced has been tested by measuring voltageand current density though at lower levels. The significance of this is that, the total energy produced depends on a combination of more materials in relation to the nature and size of the material. Hydrogen gas is also produced, but voltage and current are the major characteristics among others; in evaluating the performance an electrolytic fuel cell. And so, the measured values of voltage and current demonstrate the potentials of this technology to generate electrical energy for domestic and other purposes. In this era of technological advancement the government of the federal republic of Nigeria can wake to the task by diversifying electricity generation for her fast growing population using biomass materials which are hugely deposited across the country. Fuel cell technology is vast as it also produces other bi-products/chemicals that are used for the production of organic fertilizer, which enhances agricultural production and development. It is clean and safe, with little or no environmental pollution. However, in order to ensure high efficiency, reliability, functionality and low cost of the end product, proper materials must be selected in relation to correct physical parameters such as topology, shape porosity and so on. Fuel cell technology is yet to be fully harnessed in Nigeria. This work provides a guide for use of available and improvised material for construction and performance measurement of fuel cells thus charting a course for use of hydrogen as energy storage medium in Nigeria. An indigenized capacity for building electrolytic fuel cells was highlighted in this work.

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