DESIGN AND PRODUCTION OF A PROTON EXCHANGE MEMBRANE FUEL CELL FOR THE PRODUCTION OF BROWN’S GAS

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By

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DECLARATION

This thesis is the result of research work undertaken by Samuel Pamford Kojo Essuman in the department of Nuclear Engineering, University of Ghana, under the supervision of Dr. Andrew Nyamful and Dr. Vincent Agbodemegbe.

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ABSTRACT

The use of petroleum products (fossil fuels) has raised a lot of environmental concerns over the past years. This is due to the fact that most of the machines and devices manufactured are engineered to use these conventional fuels which include petrol, diesel and natural gas. However, these fuels substances pollute and deteriorate the quality of the environment. Some of these pollutants include sulphur oxides, nitrogen oxides, particulate matter, and ozone.

These gases are called greenhouse gases because they contribute to the greenhouse effect. These gases also cause depletion of the ozone layer. In the search for alternative fuels, researchers have used improved technologies such as steam reforming, partial oxidation, and electrolysis among many to produce hydrogen gas. Hydrogen gas is used in modern times for varied applications in industries and is now been considered as a viable primary fuel for the future.

Meanwhile, all these methods produce impure hydrogen except electrolysis of water. Electrolysis of water produces hydrogen and oxygen as products gases. A collection of these gases through a common outlet gives rise to a unique type of gas called Brown's or oxyhydrogen gas. Brown's gas is a mixture of oxygen and hydrogen bonded magnetically in a ratio of 1:2. In the automobile industry, Brown's gas is used as a fuel supplement to gasoline in internal combustion engines (ICEs), as well as welding and cutting of iron plates in the fabrication sector.

In this project, a fabricated oxyhydrogen generator was used to produce Brown's gas from distilled water using three selected catalyst namely caustic soda (KOH), sodium hydroxide (NaOH) and sodium bicarbonate ($NaHCO_3$). Parameters that influence the yield of oxyhydrogen gas were further studied. It was observed that increasing in the number of electrodes, catalyst concentration, voltage and time increased the yield of oxyhydrogen gas production.

With the rapid increase in consumption of fossil fuels and its high contribution to environmental pollution, this project also sought to improve emissions of internal combustion engines characteristics. This was performed by using oxyhydrogen gas produced in the laboratory. The results showed a drastic reduction in the concentration of CO, NO_x, Total Hydrocarbon (THCs) and SO_2 and a subsequent increase in engine performance and efficiency.

The application of oxyhydrogen gas as a fuel supplement for Spark and Compression Internal Engines was considered to be one of the most desirable methods to ensuring green environment. Oxyhydrogen gas has many excellent combustion properties that can be used to improve hydrocarbon combustion and emission performance of automobile engines.

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CHAPTER 1

INTRODUCTION

Transportation of goods and humans are inevitable activity in any country. To ensure sustainable economic and social growth as well as efficient trade between countries, transportation is key. The use of conventional fuels in the transport sector is enormous. In Ghana, 5 to 7% of crude oil is used annually (Emmanuel K. et al., 2012). The use of crude oil in the transportation sector has, therefore, become an essential socio-economic factor to national development. The Bank of Ghana in 2012 mentioned that transportation accounts for 23.9% of the total energy demand in Ghana (Armah, 2002). However, most of the automobiles are engineered to use conventional fuels like diesel, petrol, gasoline and natural gas.

With the continuous depletion of petroleum reserves, prices of fossil fuels at the world market are not stable. Subsequently, because of the huge dependency of the transport industry as well as the thermal generation sector on imported fossil fuels, Ghana has been witnessing supply and price volatilities in recent years.

This has called for the search for alternative fuels that can be produced locally with low price impact on the economy as well as been renewable, abundant and environmentally friendly. This study is therefore directed at the production of such an alternative fuel.

1.1 Problem Statement

The combustion of petroleum-derived fuel in the power generation sector, transportation industry, and agricultural sector has resulted in the emission of a large amount of air pollutants. The continuous use of these fuels has therefore necessitated for stringent environmental regulations such as the Kyoto protocols which restrict gaseous emissions such as carbon monoxide (CO), oxides of Sulphur and nitrogen, air particulate and unburned hydrocarbons. These pollutants are considered to have a negative effect on the environment and these are summarized in Table1.

Table 1: Summary of effect of use of conventional fuel pollutants (Armor, 1999)

Type of gas	Environmental Impact
Carbon monoxide (CO)	CO combines with haemoglobin to form carboxyhaemoglobin. Effects of CO include headaches, nausea and lethargy.
Suspended air particles	High degree mortality from cardiovascular and respiratory diseases.
Sulphur dioxide (SO_2)	Causes acid rain that impact negatively on vegetation and building materials.
Unburnt hydrocarbons	Causes acid rain that impact negatively on vegetation and building materials.
Oxides of nitrogen (NO_x)	Contributes to regional air pollution which serves as reactant for production of photochemical smog and also contributes to acid rain
Ozone	This causes breathing difficulties, headaches, aggravate respiratory problems and causes excessive fatigue in humans.

Additionally, the use of conventional fuels aside the environmental problems discussed is also found in our energy sector. In Ghana, over 45% of our total electricity generation comes from thermal sources. Due to oil price fluctuations at the world market, most of these plants are not able to stay in full operation.

As energy use in Ghana is tied to population growth, industrialization, expansion of urban centers through rural electrification, development of industries and infrastructural facilities, the unavailability of power would, therefore, cause most businesses to fold-up leading to high unemployment rate and also poor quality of life.

To avert this situation, it is important that the country looks for other alternative source of fuel that can be produced in large amount to serve its industries as well as other commercial operations and can be produced locally in the country using local materials.

1.2 Justification

The automobile industry has been advancing at an exponential rate over the past decade. At the same rate, the world is witnessing depletion of fossil fuel reserves and increase in the emission of unburnt hydrocarbons. Technology has been used to improve the design, increase engine power and also at making automobiles fuel efficient. Researches have been initialized to find alternatives, cleaner and sustainable renewable source of energy such as electric cars, hybrid vehicles and solar powered vehicles. But these are sometimes unreliable. Currently, gasoline is been considered as a universally accepted and sustainable fuel. However, over the years the depletion of petroleum reserves has had consequence effect on transportation costs due to over dependency on fossil fuel. This situation is not an exception in Ghana. As discussed earlier, excessive pollution due to the use of fossil fuels has led to catastrophic environmental changes, global warming, and other ecological imbalances. This has therefore called for an urgent need to conserve petroleum reserves while other options are been looked at.

Oxyhydrogen (HHO) gas produced via water electrolysis in an HHO generator is seen as a promising fuel supplement to gasoline which can be used to support combustion. HHO gas has a high calorific value which when injected with petrol, readily combust resulting in the reduction of fuel consumption and increase in engine efficiency. Increase in oxygen levels when using oxyhydrogen gas results in much cleaner combustion and hence the exhaust emission has lesser traces of NOx, CO, CO_2 as well as THCs (Ibrahim M.A.L., 2006). The results also indicate an increase in thermal efficiency, reduction in exhaust emission and cleaner engine manifold without any drastic change in the engines of current automobiles.

Accordingly, the addition of oxyhydrogen gas to conventional fuel mixtures increase their octane numbers. The octane number is usually used for fuel classification in the petroleum industry.

Commercially, the justification for the use of oxyhydrogen gas could be attributed to the following reasons provided by (Mori et al., 2013);

- Oxyhydrogen gas increases car miles per gallon and fuel efficiency and hence save money.
- Oxyhydrogen gas is considered environmentally friendly because it burns releasing water as the only end product.
- Improves thermal efficiency and works on both diesel and petrol engines.

- Reduces engine noise and improves horse power.
- Oxyhydrogen gas is efficient, safe, clean & less expensive to operate.
- Oxyhydrogen gas has an implosive nature (Mori et al., 2013).
- Oxyhydrogen gas is used to melt and vaporize high-temperature materials like tungsten (Mori et al., 2013).
- Oxyhydrogen gas flame burns through blocks of materials due to its extreme directionality when used as a torch flame. This allows for precision welds. (Mori et al., 2013).

This makes oxyhydrogen gas a viable gas which can be commercially adopted as a fuel supplement or as a primary fuel for various applications.

1.3 Main Objective

To design and produce a proton exchange membrane fuel cell for the production of brown's gas as an alternative source of fuel.

1.3.1 Specific Objectives

- To select and examine various metals with good electrical conductivity based on their chemical stability, price range and corrosion resistivity.
- To sample and select catalysts with good electrical conductivities
- To evaluate the main performance parameters that affect the operation of a proton exchange membrane fuel cell.
- To build a rectifier with adjustable voltage and current.

The next chapter would deal with the physical and chemical properties of hydrogen from the perspective of safety, describe possibilities of using alternative fuels, elaborate on some selected alternative fuels with their respective advantages and disadvantages and description of the most widely used methods of hydrogen production.

CHAPTER 2

LITERATURE REVIEW

2.1 Hydrogen Gas

Hydrogen is the most abundant element on earth. However, hydrogen does not exist in its pure state. Hydrogen forms compounds with other elements and as such it is seen as an energy carrier rather than a primary fuel. Technology improvement together with research over the past years has proven that there is a possibility of hydrogen becoming the fuel for the future and this is geared towards replacing conventional fuels, especially in the car manufacturing industry as hydrogen vehicles are currently been investigated.

However, in Ghana, the use of hydrogen gas has enormous applications in our industries. These include hydro-desulphurization, fertilizer production, conversion of unsaturated fat to saturated forms, cracking of plastics, welding torches, brazing in electronics, processing of nuclear fuel and as a space rock fuel.

Nevertheless, hydrogen is an important fuel which helps resolve local problems with environmental pollution. In the car manufacturing sector, hydrogen is used as a carrier of energy necessary for propulsion. Hydrogen usage is estimated to be around 6 % every year, and this is expected to be growing at 10% per annum.

Globally, acceptable technologies including steam reforming account for the highest production of hydrogen followed by renewable resources. Hydrogen is said to be the fuel for the future because its combustion does not produce any air pollutant. Since hydrogen occurs in combine form with other elements, one of the most viable ways for its production also is the cracking of its raw materials. A common example of such element combination is water. Separation of hydrogen from water is expensive since the electrolytic process involved consumes a huge amount of energy. A feasible production in this direction is tied to the cheap production of electricity from solar, wind and water resources or from nuclear facilities. It is, therefore, necessary to find promising technologies and resources and assess the effectiveness of the production methods along with their impact on the environment.

2.2 Methods of Hydrogen Production

Commercially, technologies for hydrogen production can be classified into:

- utilizing fossil fuels;
- utilizing the joint thermal treatment of fossil fuels and selected waste organic mixtures such as waste rubber and polymers;
- utilizing biomass and water.

2.2.1 Steam Reforming

This is the most economical, cost-effective, and widely affordable method of hydrogen production (Palmová and Schöngut, 2004). The advantage of this technology is obtained from its high efficiency. In the first stage of steam reforming, the tube reactor is filled with a catalyst together with the hydrocarbon that serves as the raw material in a steam environment (Song et al., 2007). The raw material is first desulphurized to produce a lower concentration of CO_2. The entire process is considered endothermic. In the second phase, CO is converted to carbon dioxide by means of water vapor (Olaga BIXAKOVA and STRAKA, 2010). The equations for the entire process are as follows;

$$CH_4\,(g) + H_2O\,(g) \longrightarrow CO\,(g) + 3H_2(g) \qquad (1)$$

$$CH_4\,(g) + 2H_2O\,(g) \longrightarrow CO_2\,(g) + 4H_2(g) \qquad (2)$$

$$CO\,(g) + H_2O(g) \longrightarrow CO_2\,(g) + H_2\,(g) \qquad (3)$$

$$CO_2\,(g) + H_2(g) \longrightarrow CO\,(g) + H_20\,(g) \qquad (4)$$

Because CO_2 has a high affinity for steam, it dissolves in it to form carbonic acid. This acid is removed from the system by two reversible processes that are exothermic (Holladay et al., 2009). A simplified process diagram for steam reforming is as shown below.

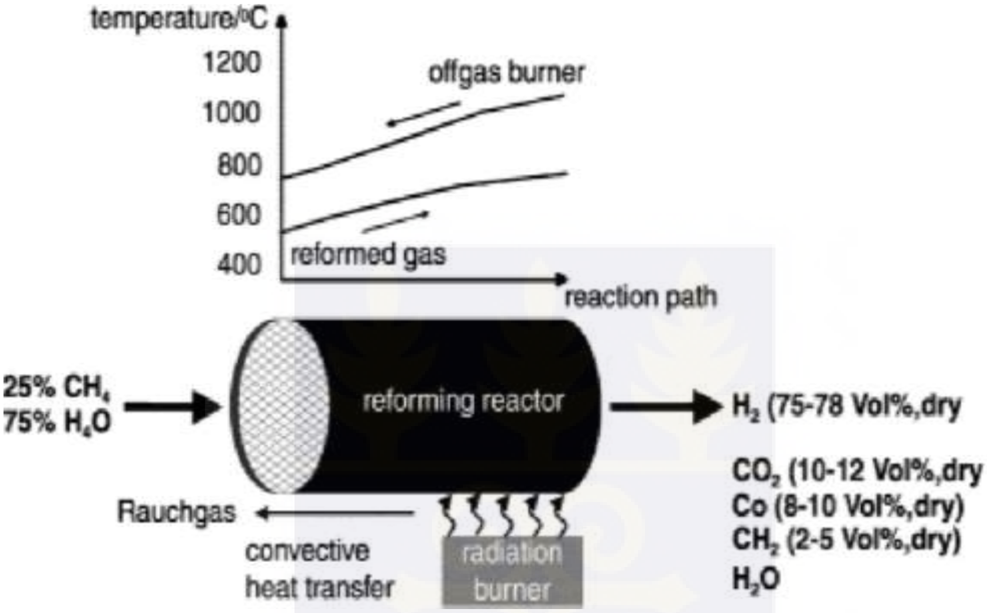


Figure 1: Diagram for steam reforming process

In steam reforming process, the raw materials are characterised by their hydrogen and carbon proportion. Higher proportions indicate lower emission of carbon dioxide. Industrially, hydrogen production by steam reforming accounts for about 85% of all hydrogen used (Holladay et al., 2009). The disadvantage of this technology is that the hydrogen produced contains a high percentage of carbon dioxide making it impure. (Olaga BIXAKOVA and STRAKA, 2010).

2.2.2 Partial Oxidation

In partial oxidation, methane is vapourized using oxygen and steam at a temperature of 1500 °C at a pressure of 4 MPa. Comparing this method to steam reforming, partial oxidation produces an enormous amount of carbon monoxide. To make this technology efficient, the carbon monoxide is transformed into carbon dioxide and hydrogen. This mechanism enables the system to be maintained at equilibrium (Holmen, 2009). The reaction equations are indicated below.

$$CH_4\,(g) + O_2\,(g) \longrightarrow CO\,(g) + 2H_2(g) \qquad (5)$$

$$CH_4\,(g) + 2O_2\,(g) \longrightarrow CO_2\,(g) + 3H_2O(l) \qquad (6)$$

$$CH_4\,(g) + H_2O\,(l) \longrightarrow CO\,(g) + 3H_2(g) \qquad (7)$$

Partial oxidation is less expensive as compared to steam reforming, but the conversion of CO to CO_2 makes this technology more expensive (Schöngut and Palmová, 2004). The efficiency of this process is between 60–75 % (Holladay et al., 2009).

2.2.3 Autothermal Reforming

Autothermal cracking makes use of water vapor and oxygen in a process called Fischer-Tropsch synthesis. The heat necessary for the production of steam for the cracking reactions in the catalytic zone is supplied by partial oxidation, i.e. by combustion of part of the raw material treated like natural gas (Holladay et al., 2009). The energy demand for the process is normally lowered using Nickel-based catalysts. The derived heat from partial oxidation minimizes the requirement of an external source of heat. The efficiency of this technology is observed to be around 70 %, which is slightly lower than that of steam reforming (Holladay et al., 2009). The equations that explain this process are indicated below.

$C_mH_n + ½\, m\, H_2O + ¼\, m\, O_2 \rightarrow m\, CO + (½\, m + ½\, n)\, H_2$ (8)

$CH_4 + H_2O + O_2 \rightarrow 3\, CO + 7\, H_2$ (9)

2.2.4 Pyrolysis and Co-Pyrolysis

In pyrolysis process, heat is added to the organic material and vaporized at a pressure and temperature of 0.4 MPa and 900 °C respectively (Ni et al., 2006). The formation of dioxins is absent in this process because the process proceeds without oxygen and air. Since carbon monoxides formation is minimal, the process does not require a secondary reactor as employed in partial oxidation (Holladay et al., 2009). As a result, this process offers a reduction in greenhouse emissions. The equation for this process is outlined below.

Organic material + heat $\rightarrow H_2 + CO + CH_4$ (10)

Pyrolysis processes can be classified into low-temperature (up to 500 °C), medium-temperature (500–800 °C) and high temperature (over 800 °C). The entire process can be slow or fast, but slow pyrolysis is not considered for hydrogen production. At high-temperature process, the initial organic material is intensely heated to a temperature of 450–550 °C with a short dwell time in the reaction zone (maximum of 2 s). The heating is ensured in various ways, e.g. the recirculation of hot sand or gases, additional combustion or hot walls. The created gaseous and liquid products are cooled as quickly as possible. The end products of pyrolysis in the fast mode comprise of all the phases, i.e. liquid, solid and gaseous substances (Ni et al., 2006). This includes;

a) liquid products (tars and oils)

b) solid products include coke and inert materials;

c) gas products (these elements: hydrogen, methane, carbon monoxide and carbon dioxide and other gas substances, which depend on the character of the organic material used).

2.3 Alternative Methods of Hydrogen Production

2.3.1 Water Electrolysis

Water splitting is an electrochemical method of obtaining hydrogen alongside oxygen. This process accounts for 4% of all production in the world (Holladay et al., 2009). During electrolysis, water is split into hydrogen and oxygen using electric current. Hydrogen is produced at the cathode (where reduction occurs) and oxygen is produced at the anode (where oxidation occurs). An electrolytic cell differs from an electrochemical cell in that in electrolysis, electricity is used during the process whiles in an electrochemical cell a chemical reaction produces electric current. Also in electrolysis, the cathode is negative and the anode is positive whiles this is opposite in electrochemical cells. The equation for the entire electrolysis process can hence be summarized by the following equations:

Cathodic reaction

$$2H_20\ (l) + 2e^- \longrightarrow H_2\ (g) + 2OH^-(aq) \qquad (11)$$

Anodic reaction

$$4OH^-(aq) \longrightarrow O_2\ (g) + 2H_20\ (l) + 4e^- \qquad (12)$$

The net reaction is $2H_2O\ (l) \longrightarrow 2H_2\ (g) + O_2\ (g)$ (13)

Electrolysis process produces no greenhouse gas but the entire process is not economically viable. This is because electrolysis is energy intensive and hence makes it difficult for commercialization. Other possible ways of making electrolysis process feasible include the use of renewable energies such as solar, the wind, hydro power and nuclear energy (Holladay et al., 2009). On the commercial front, the efficiency of water electrolysis is about 60-70 % (Kai Zeng and Dongke, 2010).

2.3.2 Alkaline Electrolyzer

An electrolyzer refers to the unit in which electrolysis of water occurs whereby current is used to split water into hydrogen and oxygen gas. The basic components of an electrolyzer include a separator, electrodes, and an electrolyte solution. An alkaline electrolyzer is, therefore, a type of electrolyzer which usually uses a base such as potassium hydroxide (KOH), and sodium hydroxide (NaOH) among many for its electrolysis process. Other viable electrolytes used aside bases are salts which include sodium chloride (NaCl) and sodium hydrogen carbonate ($NaHCO_3$).

Commercially, 25% weight of the alkaline solution is used (Turner et al., 2008). With this type of electrolyzers, water is introduced into the system via the cathode in which case the water splits into hydrogen ion and hydroxide ion respectively (Daniel Symes, 2011). The hydrogen ion reacts with electrons in solution to produce hydrogen gas at the cathode. The hydroxide ions in solution, however, undergo oxidation at the anode to give evolution of oxygen gas. The equation for the reaction is as follows;

Cathodic reaction

$2H_20\ (l) + 2e- \xrightarrow{\hspace{3cm}} H_2\ (g) + 2OH^-(aq)$ (14)

Anodic reaction

$4OH^-(aq) \xrightarrow{\hspace{3cm}} O_2\ (g) + 2H_20\ (l) + 4e-$ (15)

The net reaction is $H_2O\ (l) \xrightarrow{\hspace{3cm}} H_2\ (g) + 1/2\ O_2\ (g)$ (16)

Productivity of alkaline electrolyzers are normally between 50-60%. Electrodes employed for alkaline electrolyzers include platinum, palladium, stainless steel among many.

2.3.4 Proton Exchange in a Polymer Electrolyte Membrane Electrolyzer

This type of electrolyzers works with the principle of fuel cells. The catalytic electrodes are normally ruthenium and platinum and a Nafion membrane is used as a separator (Turner et al., 2008).Whiles water is filled to the electrolyzer via the cathode in the alkaline types, water in Proton Exchange Membrane electrolyzer is fed to the anode compartment where the splitting of the water takes place. Here hydrogen ions pass through the Nafion polymer membrane to the cathode and react with electrons to produce hydrogen gas. Subsequently, oxygen gas is produced at the anode. The efficiency of this type of electrolyzer is around 55-70% (Turner et al., 2008). The equations below depicts the reactions for the entire process.

Anodic reaction

$2H_20\ (l) \xrightarrow{\hspace{3cm}} O_2\ (g) + 4H^+ + 4e^-$ (17)

Cathodic reaction

$4H^+(aq) + 4e- \xrightarrow{\hspace{3cm}} 2H_2\ (g)$ (18)

Total net reaction is $H_2O\ (l) \xrightarrow{\qquad\qquad} H_2\ (g) + 1/2\ O_2\ (g)$ (19)

2.3.5 Solid Oxide Electrolysis Cells

The Solid oxide electrolysis cell (SOEC) is a cell that employs solid materials as its electrolyte. The cell function similarly as the alkaline electrolyzer in that oxygen ions are allowed to pass through the solid matrix whiles hydrogen ions are left in the non-reactive flow of steam. Electrons at the cathode react with the hydrogen ions to form hydrogen gas. The oxygen ions, however, form oxygen gas at the cathode leaving excess electrons in the outer circuit configuration. The solid oxide electrolyzers operate at temperatures quite higher than alkaline electrolyzers. These cells are efficient to utilize the excessive heat produced during operations at higher temperatures and accordingly reduces the consumption of electrical energy. The working temperatures for SOEC is usually between 100-150 °C. In a thermal source, SOEC efficiency can be between of 85-90% of operations.

2.3.6 Thermochemical Cracking of Water

Thermochemical cracking of water was employed when the need for production of alternative fuels occurred in 1980. In this process, water is cracked at high temperatures of about 2500 °C. The lack of development of this process over the years is due to its high temperature of operations which present difficulties in the availability of construction materials for this type of cells. However, to improve upon the systems, chemical reagents are usually used to lower the temperature at which the electrolysis process occurs. The efficiency of this system is also estimated at 50% (Funk, 2001).

2.3.7 Photoelectrolysis

This is a renewable method for producing hydrogen gas. The electrode for this process is made of a semiconductor that absorbs solar energy to provide the needed voltage for decomposition of water to hydrogen and oxygen. However, for the attainment of higher voltages, the semiconductor material and the intensity of the solar energy is very critical. Previous research indicates that at a current density of 10-30 mA/cm^2, the voltage produced by electrolysis of water is 1.35 V which exceeds the minimum voltage required for electrolysis of this type of process. This technology is still at developmental stage (Holladay et al., 2009).

2.3.8 Hydrogen from biomass

Biomass is a generic term for biological materials derived from living and non- living materials such as forest residues, animal matter and remains of commercial crops. Chemically, biomass is made up of carbon and other atoms including hydrogen. In the traditional system, biomass has been used for domestic purposes such as cooking and provision of heat for temperate zones and to the large extent electricity (J.D. Holladay et al., 2009).

Because of the progressive depletion of conventional fuel reserves, the utilization of biomass energy as a renewable energy source has gained particular interest (A.C.Caputo et al., 2005). The growing interest is driven by reasons including the following (K.S et al., 2004):

(1) alleviating poverty in developing countries,

(2) Serves as a cheaper source of energy

(3) Biomass can be used to provide form of energy

(4) it is environmentally friendly and act as carbon sinks and

(5) it helps to prevent deforestation and hence improves the quality of soil as well as maintenance of water properties

Among other utilization of biomass, hydrogen production is considered as a very important one. Comparing to other pathways of hydrogen production, that from biomass is competitive in several ways (A. Demirbas, 2008):

(1) avoidance of large importation oil by developing countries,

(2) can be produced locally within a country, and

(3) ensures low price impact on a country's economy

The general equation for hydrogen production through gasification is shown below;

$$\text{Biomass} + O_2(\text{or } H_2O) \longrightarrow CO, CO_2, H_2O, H_2, CH_4 + \text{other (e.g. tar)} + \text{ash} \qquad (20)$$

2.3.9 Biodiesel

Biodiesels are produced from sources such as soybean, grape, and coster among many for automobiles especially diesel engines. These type of fuels are environmentally friendly, degrade naturally with time and non-toxic. Vegetable oils are renewable as they are produced from vegetables. They are greener to the environment and contains no sulphur (Wang Y.D. et al., 2006).

Bio-diesel are oxygenated fuels i.e. they contain a high amount of oxygen and this enables bio-diesel to undergo complete combustion emitting no greenhouse gases such as CO, CO_2, NO_x and SO_x and other particulate matter (Murugesan A. et al., 2009).

2.3.10 Liquefied Petroleum Gas (LPG)

This type of fuel is made up of mixtures of gases in a proportionate composition. Modern constituents of liquefied petroleum gas include propane (C_3H_8), butane (C_4H_{10}), propene (C_3H_6), butanes (C_4H_8), iso-butane, and ethane (C_2H_6). The composition of commercial LPG is quite variable (Pundkar A.H. et al., 2012). Out of the total production of LPG gas, 55% and 45% comes from natural gas purification and crude oil refining respectively (U.S. Department of Energy, 2003). One of the advantages of LPG is its high octane number. The octane number of LPG increases the compression ratio of the fuel for efficient combustion.

2.3.11 Methanol

Methanol is produced commercially by distillation of wood, coal petroleum and natural gas. The raw materials for methanol production include shale, residual oil, tar sands and waste and peat (Allen C.A.W. et al., 1999). Production of methanol is done in two stages. The first stage involves gasification of the raw material with water vapor to produce a mixture of hydrogen and carbon monoxide known as syngas (Madhu et al., 2013). In the second stage, the syngas is compressed at 150 bars through a catalytic copper base process. Methanol is recommended for use due to its high performance and its resistance towards knocking in internal combustion engines (Kowalewics A., 1993).

2.3.12 Ethanol

Ethanol is a type of biofuel. Ethanol is produced via gasification of biomass or from mineral and petroleum sources. Ethanol is considered suitable for internal combustion engines due to its high octane number and flame speed. Demerits of ethanol for commercial use in automobiles include low heating value and its corrosiveness to metal and plastic parts of car engines. Also, large production of ethanol is not economical since it might have a negative impact on food availability and agriculture in general (Ahmed Taha. et al., 2013).

2.4 Electrical Circuit Analysis of Electrolytic Cells

For an electrochemical reaction to proceed, a number of barriers have to be overcome. These require sufficient electrical energy supply. These barriers include the electrical resistance of the circuit, activation energies of the electrochemical reactions occurring on the surfaces of the electrodes, availability of electrode surfaces due to partial coverage by gas bubbles formed and the resistances to the ionic transfer within the electrolyte solution. It is important that these barriers are analyzed in the context of thermodynamics and kinetics as well as transport process principles.

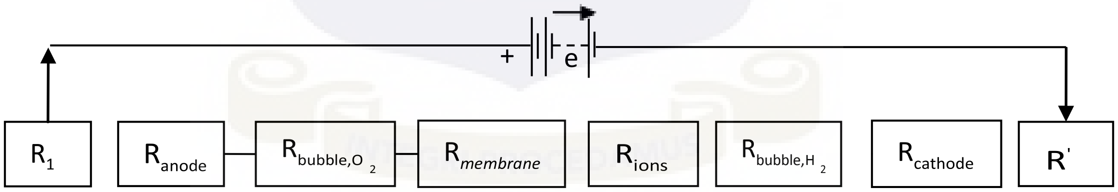


Figure 2: An electrical circuit analogy of resistance in the water electrolysis system

Figure 2 illustrates the resistances (the barriers) offered in an average water electrolysis device. The first resistance $R_1$is the external electrical circuit resistance together with the wiring and connections at the anode. R_{anode} is originated from the overpotential of the oxygen evolution response at the surface of the anode. $R_{bubble\ O2}$ is the resistance due to partial coverage of the anode by way of the oxygen bubbles, hindering the interaction between the anode and the electrolyte. The resistances that come from the electrolyte and the membrane are noted as R_{ions} and $R_{membrane}$ respectively. In addition, $R_{bubbles,\ H2}$ roots from the blockage of the cathode by hydrogen bubbles, $R_{cathode}$ is the resistance due to the overpotential for the oxygen evolution reaction and R'_1 is the electric resistance of the wiring and connections at the cathode. For this reason, the whole resistance can be expressed in the equation below;

$$R_{Total} = R_1 + R_{anode} + R_{bubble,O2} + R + R_{ions} + R_{membrane} + R_{bubble,H2} + R \quad \textbf{(21)}$$

These resistances in electrolysis can be categorized into three classes. These are electrical resistances; response resistances; and transport resistances.

2.4.1 Electrical Resistances

Ohm's law is generally used to calculate the electrical resistances of electrolytic cells. This equation is expressed as:

$$R = U / I \qquad (22)$$

Where, I and U represent the current and voltage respectively (Kai Zeng and Dongke, 2010). Nevertheless, the total resistance associated with electrolysis can also be written as:

$$R = L / (\rho A), \qquad (23)$$

Where, L, ρ *and* A, are the length, specific conductivity and the cross-sectional area of the conductor respectively. Electrolysis processes are considered inefficient because factors like transport resistance cause excessive heat. The ohmic loss is hence defined as the loss of energy due to the effects of these resistances (Oldham and Myland, 1993).

2.4.2 Electrochemical Reaction Resistances

These are the chemical resistances that occur due to the overpotentials required to control the activation energies of the hydrogen and oxygen formation reactions on the cathode and anode surfaces. These are the inherent strength limitations of the reactions determining the kinetics of the electrochemical reactions whose rates can be expressed with the aid of the Arrhenius law (Bard and Faulkner, 2001).

Simply put, the techniques in any effort to enhance the power performance of water electrolysis and hence the overall performance of the system need to involve information of these resistances in order to minimize them. It is therefore critical to be aware of the origins of these resistances and to quantify these resistances to enable one decide which resistances are the most important and well worth getting to study.

2.5 Thermodynamic Consideration

Thermodynamically, water is one of the stable substances in the universe which require a large amount of energy to split. To split water there is a minimum voltage to be overcome. This voltage is called the electromotive force. The cell voltage is defined as the equilibrium potential difference between the cathode and anode plates (Wendt and Kreysa, 1999).

$$E° = E°_{anode} - E°_{cathode} \qquad (24)$$

However, for the spontaneity of any chemical reaction, the cell voltage is related to the Gibbs free energy. This relation is given by;

$$\Delta G = nFE° \qquad (25)$$

Where, n, F, and $E°$ are the number of moles of electrons involved in the reaction, Faraday constant and the standard cell voltage respectively. At 298K, the standard potential of water electrolysis is 1.23V which gives a Gibbs free energy of + 237.2 kJ/mol. This Gibbs free energy defines the minimum amount of energy required to produce hydrogen and oxygen from water (Kim *et al*, 2006). To maintain the electrochemical reaction without desorption or heat generation, the thermo-neutral voltage is required to be maintained. (Leroy *et al*, 1980). This is illustrated in figure 3 and 4.

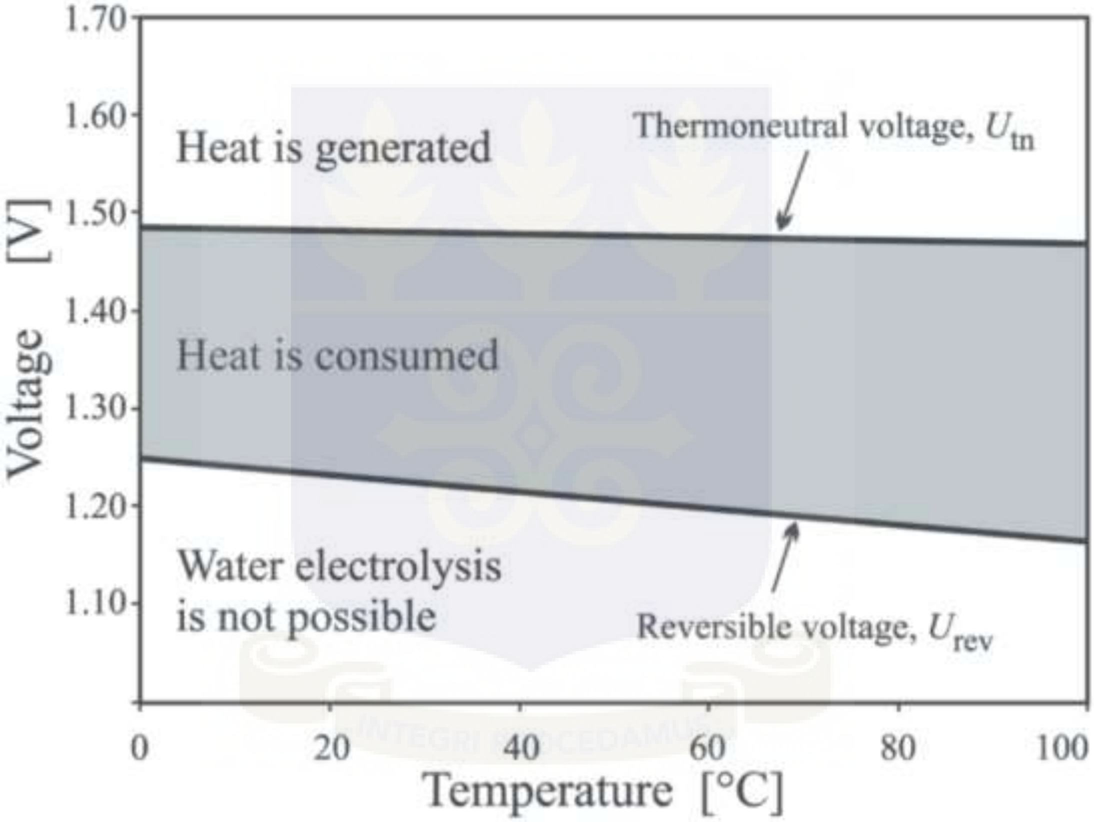


Figure 3: Reversible and thermo-neutral voltage for water electrolysis as a function of temperature at a pressure of 1 bar

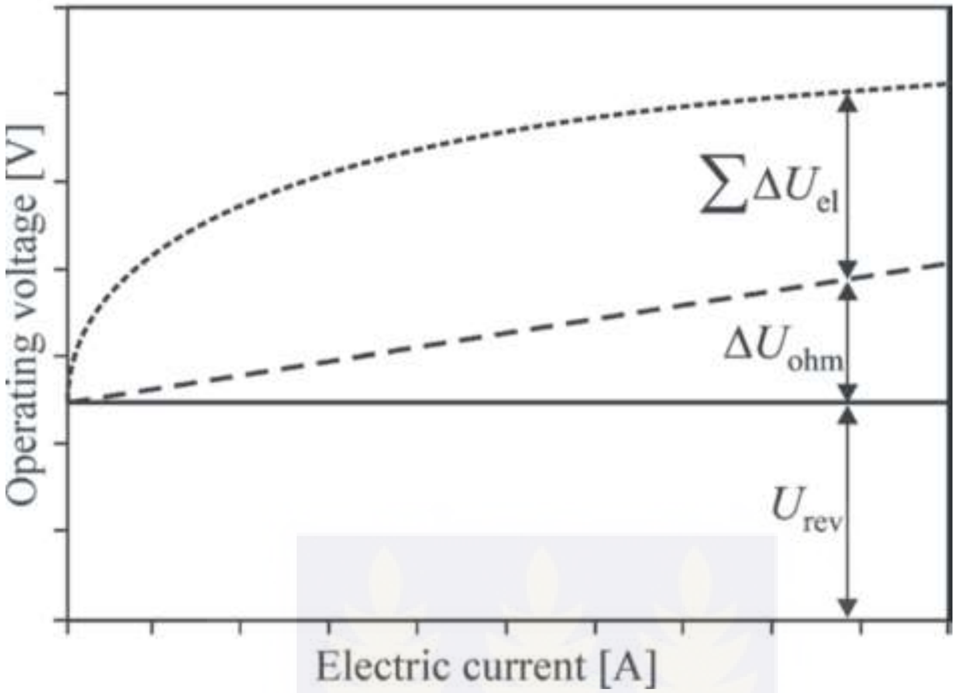


Figure 4: Contribution of individual (over)voltage to the operating (actual) voltage of the electrolytic cell

2.5.1 Cell Efficiencies

The efficiency of any electrolysis process is defined as the percentage share of the energy output to the total energy input (Bockris *et al*, 1981). Generally, for a typical electrolysis system, the voltage efficiency is given by;

$$\% \text{ Voltage Efficiency} = \frac{(\text{E anode} - \text{Ecathode})x\ 100}{\text{E cell}} \quad (26)$$

This gives the value of the excess voltage used to split water into hydrogen and oxygen. Moreover, two types of efficiency can be identified in water electrolysis. These are Faradic efficiency and Thermal efficiency. Both efficiencies are expressed as;

$$\eta Faradic = \frac{\Delta G}{\Delta \text{G+Losses}} = E(\Delta G)/E(cell) \quad (27)$$

$$\eta Thermal = \frac{\Delta H}{\Delta \text{H+Losses}} = E(\Delta H)/E(cell) \quad (28)$$

Where the E_{cell} , $E_{\Delta G}$ and $E_{\Delta H}$ are the cell voltage, equilibrium and the thermo-neutral voltages, respectively. When the electrolytic process absorbs heat from the surroundings, the system gives an efficiency greater than 100%.

Since there is a lot of loss during the process, the Faradic efficiency is always less than 1 whiles the thermal efficiency can be greater than 1 if the process proceeds with a voltage lower than that of the thermos-neutral voltage. Another means of evaluating the efficiency of an electrolysis process is done by considering the yield of hydrogen production to the electrical power input. This expression is mathematically expressed as;

$$\eta_{H2}\,\text{production rate} = \frac{r\text{H2}\; production\; rate}{\Delta\, E} = V\,(m^3\,h^{-1})/U_i\,(kJ) \qquad (29)$$

Where, the U_j, ΔE, and V are the cell voltage, electrical power input, and the hydrogen production rate at unit volume electrolysis cell.

Additionally, energy efficiency can also be calculated by deducting the total energy losses from the total energy input as indicated below.

$$\eta_{H2}\,\text{yield} = 1 - \frac{E\;loss}{E\;input} \qquad (30)$$

2.5.2 Electrode Kinetics

The current density and the nature of electrode surfaces influence the rate of a chemical reaction as well as the composition of the electrolyte solution. During a typical reaction in solution, ions near the electrodes in solution form a double layer (Oldham and Myland, 1993). In addition, the electrode potential characterized by the reaction overpotential determines the rate of the entire chemical process. The correlation between surface overpotential, the composition of solution ions and current density helps to study electrode kinetics (Newman, 1991). As illustrated in Figure 5, the ions close to the electrode surface forms an ordered layer called the inner Helmholtz layer (IHL). The unordered ions form the outer Helmholtz layer (OHL) (Pickett, 1979). When the way in which the ions are distributed across the surface of the electrode is plotted with electrode area, it was observed that a potential difference develops between the solutions and the electrode surface due to the existence of the double layer (Wendt and Kreysa, 1999).

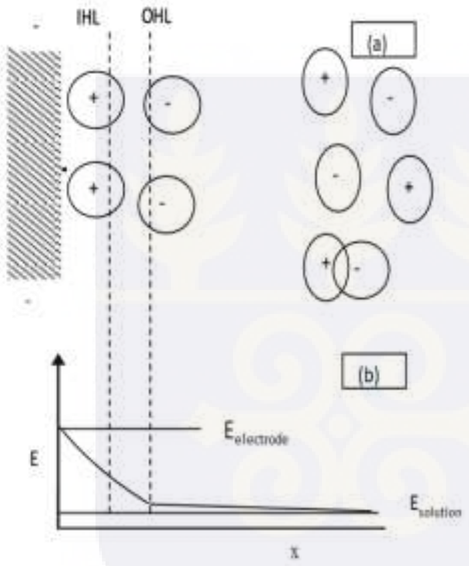


Figure 5: Diagram of electrical double layer and the potential distribution near an electrode surface

In electrode kinetic processes, Faraday states that the amount of species in moles electrolyzed (H^+ or O^{2-}), N is expressed as;

$$N = \frac{Q}{nF} \tag{31}$$

Where Q, n and F are the number of coulombs, number of electrons consumed in the chemical reaction and F is Faraday’s constant.

To determine the rate constant of a reaction, the Arrhenius equation is generally used.

$$k= Ae^{-E_A/RT} \qquad (32)$$

Where A is the frequency factor, E_A is the activation energy in kJ.mol, R is the universal gas constant, and T is reaction temperature (Qinhui Wang, 2012). Despite the simplicity of this equation, the expression is able to illustrate the correlation between the activation energy and the rate constant.

2.5.3 Hydrogen Generation Overpotential

The process of hydrogen formation is said to be in three phases which involve adsorption, chemical desorption, and electrochemical desorption. In the adsorption process, hydrogen ion reacts with an electron to form a neutral adsorbed atom followed the chemical adsorption whereby two adsorbed hydrogen atoms react to form hydrogen gas. In the electrochemical process, a hydrogen ion reacts with an electron and an adsorbed hydrogen to form one mole of hydrogen gas. Equations supporting these processes are shown below (Bockris *et al*, 1981).

$$H^+(aq) + e^- \longrightarrow H_{ads}(aq) \qquad (33)$$

$$2\,H_{ads}(aq) \longrightarrow H_2(g) \qquad (34)$$

$$H_{ads}(aq) + e^- + H^+(aq) \longrightarrow H_2(g) \qquad (35)$$

Where by the subscript *ads* represents the adsorbed status. The Tafel equation is accordingly used to evaluate the overpotential of hydrogen. This overpotential describes the additional energy barrier needed to be overcome before hydrogen gas forms in solution. The overpotential is, however, influenced by the type and concentration of catalyst, the properties of the electrode and temperature.

2.5.4 Oxygen Generation Overpotential

The path way to the formation of oxygen is more complex than that for hydrogen. In this process, an adsorbed hydroxide ion releases its electron to form a neutral adsorbed hydroxide. This adsorbed hydroxide ion then react with another hydroxide ion to form an adsorbed oxygen atoms and water. Finally, two adsorbed oxygen atoms combine to form one mole of oxygen gas. The three step mechanisms are illustrated below.

$$OH^-(aq) \longrightarrow OH_{ads}(aq) + e^- \qquad (35)$$

$$OH^-(aq) + OH^-_{ads}(aq) \longrightarrow O_{ads}(aq) + H_2O(l) + e^- \qquad (36)$$

$$O_{ads}(aq) + O_{ads}(aq) \longrightarrow O_2(g) \qquad (37)$$

The general Tafel equation used to measure the overpotential of both hydrogen and oxygen formation mechanism is given below;

$$H_{cathode} = 2.3\,[RT/\,(1-\alpha F)]\,\log\,(i/i_o) \qquad (38)$$

Where, T is the temperature in Kelvin, R is the universal gas constant, α is the charge transfer coefficient usually between 0 and 1, F is the Faraday’s constant, i is the current density in A/m^2 and i_0 is the exchange current density in A/m^2. Figure 6 shows the graph of overpotential and exchange current density.

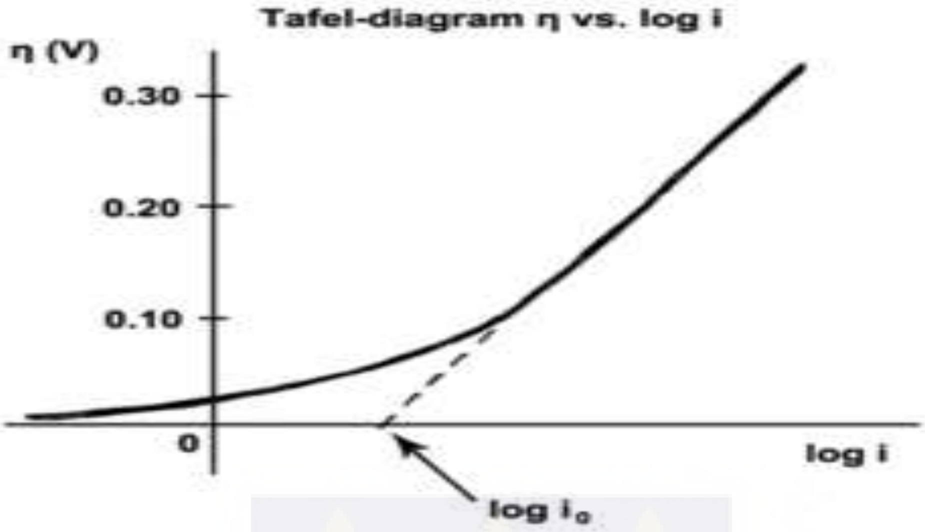


Figure 6: Graph of overpotential and exchange current density

2.5.5 Electrochemical Reaction Resistances

Electrical Resistances

The energy loss in a system can be attributed to electrical resistances. In water electrolysis, electrical resistances can be categorized into three using the principles of ohms law. These are;

1. Circuit resistances
2. Effect of ion mobility in the catalyst solution
3. Electrode coverage by gas bubbles

The types and dimension of substances and mobility of individual components determine the electrode and connection circuits. The relationship between this circuits can be expressed as;

$$R = \Sigma\ (l/Ak_g) \qquad (39)$$

Where *k* is the electrical conductivity ($\Omega^{-1}\cdot m^{-1}$), '*g*' is the electrical circuit component and A is the surface area.

However, movement of ions within the catalytic solution is influenced by the concentration of electrolyte and the distance between the cathode and anode and the separator between them. This movement is characterized by the term Molar conductivity expressed mathematically as;

$$\Lambda_c = \frac{\kappa}{C} \tag{40}$$

Where *k* and C are the conductivity and concentration of the electrolyte respectively. Molar conductivity is measured in $m^2 \cdot \Omega^{-1}$ /mol. Since strong catalyst such as inorganic bases, acids, and salts are used in electrolysis of water, it is imperative to determine the empirical relationship between concentration and molar conductivity. This relation is expressed as;

$$\Lambda_C = \Lambda_o - k\, C^{1/2} \tag{41}$$

Where in this case, *k* is the Kohlrausch coefficient and Λ_0 is the mole conductivity (Rieger, 1987).

Transport Resistances

As discussed earlier, movement of gases and liquids are important to the study of heat dissipation and distribution in the characterization of bubbles in any electrolytic solution. These factors are also affected by field flow and viscosity. During water electrolysis, increase in electrolyte concentration increase viscosity.

Nonetheless, the mobility rate of ions in solution does not necessarily increase the yield of hydrogen production. Despite the assertion that ion transport has a direct increase in reaction rate, this situation reduces the interaction between the electrodes and the solution.

Therefore a better way to ensure that this effect does not result in the build of cell overpotential is to agitate or recirculate the solution. This electrolyte recirculation can be used to increase the temperature of the solution to about 85°C (Dyer, 1985, Kinoshita, 1992).

2.5.6 Bubble Phenomena

During electrolysis, hydrogen and oxygen gas are produced. These gases tend to attach themselves strongly to the surface of the electrodes. As the hydrogen and oxygen gas bubbles grow large in size they detach themselves from the electrode. Attachment of the bubbles to the electrode increases the electrical resistance of the system. This is due to the fact that the contact between the electrode and the solution is limited, reducing electron flow and accordingly increase the ohmic resistance. The search to understanding bubble phenomena is therefore very critical in water electrolysis. Manual stirring of the solution can dislodge the bubbles to minimize the system resistance. In recent times, reducing the surface tension of the bubbles using additives is much preferred. Using these chemicals modifies the surface tension of the bubbles to be less attracted to the electrode surface. The study of bubbles in solution enables one to understand bubble detachment. Thermodynamically, the contact between the electrode, gas bubbles and catalyst at a phase angle at a boundary is shown below (Defay and Prigogine, 1966).

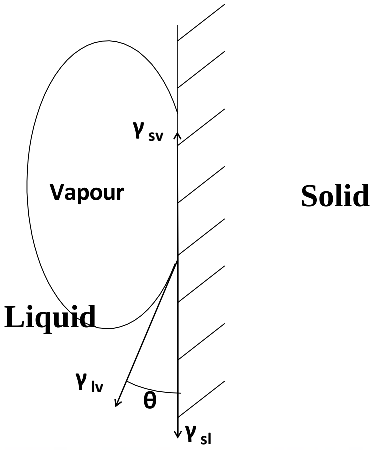


Figure 7: An illustration of the contact angle at the three phase boundary of the gas bubble, electrode, and the electrolyte

The equation below defines Young's equation in terms of contact angle and surface tension (Adam, 1968).

$$\cos\theta = \frac{\gamma SG - \gamma SL}{\gamma LG} \qquad (42)$$

Where, γ_{SG}, γ_{SL}, and γ_{LG} are the surface tensions of the solid/gas, solid/liquid, and liquid/gas interfaces respectively. The energy change accompanying these interactions is given by;

$$\Delta G = \gamma_{LG}(\cos\theta - 1) \qquad (43)$$

In addition, the wettability principle also determines the detachment of bubbles from a surface (Matsushima *et al*, 2003). According to this principle, electrode surfaces can be classified into two main types. These are hydrophilic and hydrophobic. Surfaces that interacts with water are termed hydrophilic surfaces. The hydrophilic nature of the electrode must hence be reduced to prevent attachment of bubbles to surfaces. Approaches to mitigate bubble attachment include;

1. Making the electrode surface to be more hydrophilic by surface treatment to attract water instead of bubbles.
2. Using additives to reduce the surface tension of the bubbles
3. Managing the pattern flow to mechanically force the bubbles away from the electrode surface.

2.6 Types of Oxy-hydrogen (HHO) Generators

An Oxyhydrogen generator is an electrolytic generator used to split water into hydrogen and oxygen via electrolysis process. Practically, there are two types, namely;

1. Dry cell generator and
2. Wet cell generator.

2.6.1 Dry Cell Generators

Dry cell generators have their electrodes and electrical connections sealed and protected from the electrolyte solution. Here each plate is separated from each other by a gasket. The gasket is usually used to prevent leakage during the electrolytic process. There is a reservoir tank placed at a height above the generator that serves it with an electrolyte solution. When the generator is connected to a source of power, electric current flows through the electrolyte. Hydrogen and oxygen gas are produced at the cathode and anode respectively. These gases are then collected via a common outlet back into the tank. Once the tank is filled with HHO gas, electrolyte gets pressurized and flows back into the generator again. Due to the circulation process within the system, the total heat generation is reduced. This, therefore, improves the efficiency of the system minimizing energy consumption.

2.6.2 Wet Cell Generators

With the wet cell generator, the stacked plates with gaskets are placed in the selected electrolyte solution and the end electrodes are connected to a source of power. Corrosion of the plates is massive in this type of generators because the neutral plates and the electrodes are fully immense inside the solution where oxygen gas surrounds the cathode to react with the plate resulting in the gradual wearing of the plates with time (Smith and Jerry, 2012). Since the whole set up is placed in solution, the rate of heat dissipation is low as compared to dry cell generator making the efficiency low.

2.6.3 Configuration of HHO Generators

Oxy-hydrogen can be constructed with different polarities depending on market demands. However, for higher production of oxyhydrogen gas, it is advised that the number of negative electrodes exceeds the positive electrodes. This is preferred because per the basis of water electrolysis, hydrogen gas is produced at the cathode and oxygen gas at the anode as indicated in equations 44-46 below.

$$2H_20\ (l) + 2e^- \longrightarrow H_2\ (g) + 2OH^-\ (aq)\ \text{(Cathodic reaction)} \qquad (44)$$

$$4OH^-\ (aq) \longrightarrow 2H_2O\ (l) + O_2\ (g) + 4e^-\ \text{(Anodic reaction)} \qquad (45)$$

$$2\ H_20\ (l) \longrightarrow 2H_2\ (g) + O_2\ (g)\ \text{(Overall reaction)} \qquad (46)$$

Therefore, increasing the cathode plate increases the hydrogen gas yield to bond with oxygen gas molecularly and magnetically to form an oxyhydrogen gas. Therefore, in a standard series of HHO gas, 66% of hydrogen and 33.3% of oxygen is produced.

2.7 Uses of neutral plates in HHO Configurations

Neutral plates are generally defined as plates added to an oxyhydrogen generator to lower the voltage across the positive and negative plates. From the basis of thermodynamics of water electrolysis, the minimum amount of potential difference required to split water is 1.23V with an optimum operating voltage of 2.25V. Any applied voltage above this range is converted into excessive heat by the system which affects immensely the efficiency of the HHO generator. Hence to improve the performance of the generator, neutral plates are normally used to vary the applied voltage for effective energy consumption and to prevent excessive heat generation in the entire system.

2.8 Calculating the potential difference across plates of the HHO generator

The voltage across any two plates in an oxyhydrogen generator configuration can be calculated using the formula;

$$V_n = \frac{V_0 \mathrm{n}}{[n^2+[(2\mathrm{n}-\mathrm{q}-1)\mathrm{d}]} \qquad (47)$$

Where V_o is the applied voltage from the main source, n is the number of neutral plates proposed for use, d is the common difference derived from the number of plate’s series and q is correction factor given by (n-d). The values of n, d, and q can be derived from the table 2 below for experimental purposes.

Table 2: Deduced experimental values for calculating expected cell potential

n-value	1	2	3	n_∞
d-value	1	1	1	d_∞
q-value	0	1	2	q_∞

Example, for a typical HHO gas generator with 11 plates (2 negatives, 1 positive and 8 neutrals) proposed to operate on a 20V power source, the voltage across two cells of the generator can be calculated as;

$$V_8 = \frac{20\ x\ 8}{[8^2+[(2.8-7-1)1]} = 160/72 = 2.22\text{ V}$$

Where the values of n, d, and q used were 8, 1 and 7 respectively.

2.9 Factors that influence oxyhydrogen production

2.9.1 Electrolyte quality

In the production of oxyhydrogen gas, various catalysts are added to water to enhance its electrical conductivity. Commercially, selected available catalyst used for this type of operations generally include bases, acids, and salts (TS De Silva et al., 2015). The use of these catalysts is however minimized due to their potential corrosion effects on materials used to fabricate the electrolyzer. Potassium hydroxide is, however, highly recommended for electrolyzers because of its high efficiency. Normally 27 % weight aqueous solution of KOH is used in industrial operations (Lee TS., 1971). Aside from the use of bases and acids, the introduction of salts usually introduces impurities into a solution that result in many unwanted side reactions. These impurities are mainly obtained from salts of magnesium, chloride and calcium (Wang Sheng, et al., 2007). The concern here is that impurities passivate the surfaces of plates thereby reducing the electrode - electron interaction. This turn to reduce the yield of oxyhydrogen gas and causes an increase in ohmic resistance.

2.9.2 Temperature

Temperature is known to influence reaction rate as well as energy consumption. Water splitting is more improved at higher temperatures (Davis HJ. et al, 1984). This can be explained using electrode kinetics. At higher temperatures, the mobility of ions in solution increases rapidly, due to a reduction in voltage and surface tension of the solution (M. P. Marceta et al., 2003).

2.9.3 Pressure

Pressure has been experimented to have a direct link to temperature. Increase in pressure of an electrolytic process lessons the systems energy consumption. Pressure increase also has an effect on the gas bubbles and hence causes drop in ohmic voltage and energy loss (Appleby et al., (1978). However, excessive increase in pressure to some extent have no via impact on a system.

2.9.4 Electrical resistance of the electrolyte

Electrical resistance (R) is directly proportional to the resistivity (ρ) of a system and the path through which current traveled (l) and inversely proportional to surface area (A). This relation is expressed below.

$$R= (\rho l)/A \qquad (48)$$

During an electrolytic process ions and electrons flows from one plate to another. This means that when the resistivity of the material used for the electrode is low and are close to each other, the electrons and ions in solution tend to experience less flow resistance when the electrode is placed close to each other. This is fundamental to the selection of electrode materials and the engineering to employ when constructing an oxyhydrogen generator.

2.9.5 Space between the electrodes

From the resistivity equation 48 above, it can be acknowledged that, as the distance between the electrodes reduces, the electrical resistance lowers. Studies made show that for a typical oxyhydrogen generator, the standard maximum spacing between any two plates must be between (2- 3) mm and placing the plates too close also affect the efficiency of the electrolytic process (LeRoy et al., 1979).

2.9.6 Size and alignment of the electrodes

Larger surface area is known to reduce electrical resistance. When resistivity is low, the rate of heat dissipation becomes low increasing the efficiency of the entire system. However, the alignment of the plates is also observed to have a significant effect on oxyhydrogen yield. Higher gas production can be obtained when the plates are placed in a vertical position.

2.9.7 Forcing the bubbles to leave

The covering of electrode surfaces by hydrogen and oxygen molecules is well known in studies as a phenomena that vary the ohmic resistance in electrolysis. This has also been demonstrated to decrease electrical conductivity (K. Qian et.al. 1998). For example, Figure 8 depicts how each gas molecule detaches itself and travels in solution at a distance of l_i.

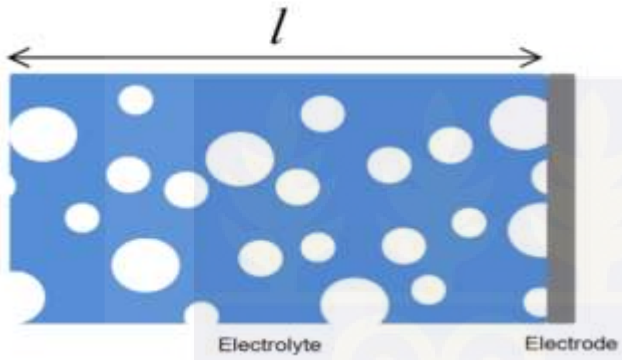


Figure 8: The formation of void fraction

Taking this into consideration, the total contribution from each gas bubbles to the overall electrolyte solution is;

$$R=\rho\,(\Sigma\, l_i)\,/A \qquad (49)$$

Methods that are currently employed to disengage gas bubbles from electrode surfaces include the use of ultrasonic field and gravity field. These methods have been observed to improve the overall efficiency of electrolysis process (De Li et al. (2009).

2.9.8 Electrode material and properties

The performance and production of oxyhydrogen gas in a typical electrolysis process is significantly impacted by the nature of electrode material used. This is because every material has its own physical and chemical property that are categorized in terms of electrical resistance, corrosion resistivity, and activity. Studies have shown that gold and platinum are two metals known to have improved properties. However, in an economic sense, these metals are expensive and hence their commercial use is limited. In alkaline electrolyzers, the most commonly used ones are Nickel, Stainless Steel, Aluminum, and cobalt. These metals are selected based on their chemical stability, price range and corrosion resistivity (Talapatra S, et al., 2010). Figures 9 and 10 show some selected metals and their respective decomposition potential and unit cost as well as their individual current densities.

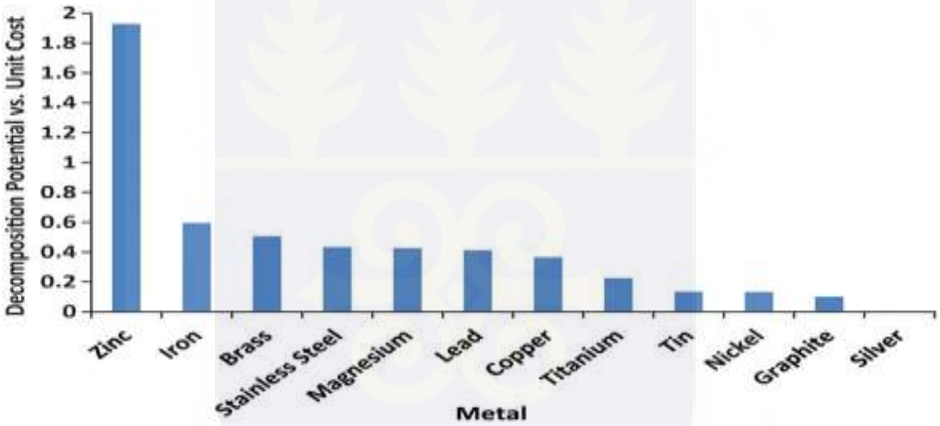


Figure 9: Decomposition potential of electrode materials as a function of material cost.

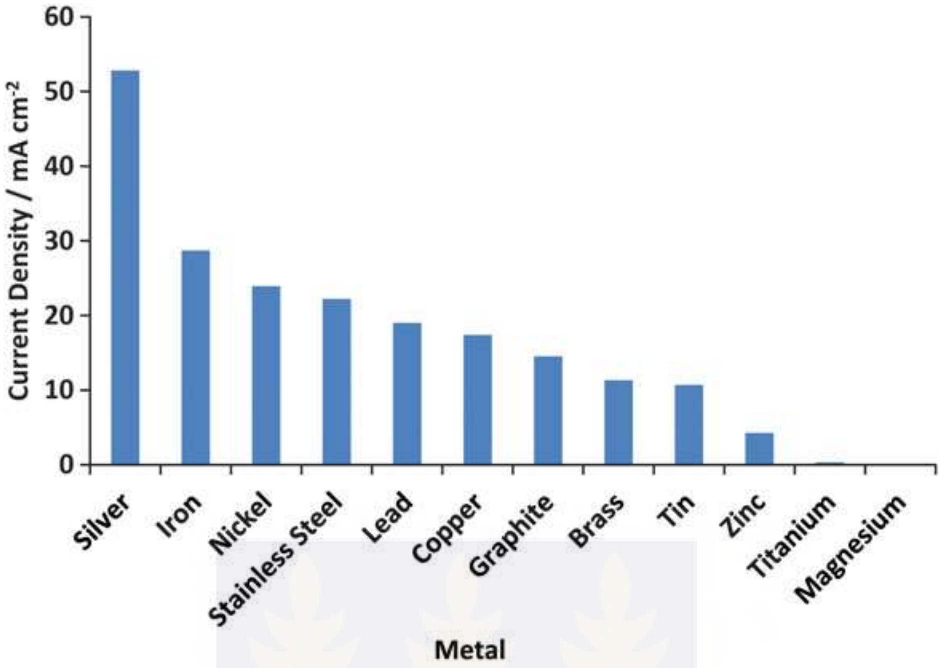


Figure 10: Current density of electrode materials at 12 V.

2.9.9 Separator material

The use of a separator in an alkaline electrolysis was studied to limit free movement of charges ions in solution. This phenomenon causes an increase in the number of gas bubbles in solution (Pickett DJ, 1979). Physical and chemical characteristics of the system such as temperature, pressure, and corrosion determine the electrical resistivity of most separators. One prominent separator used in the early development of electrolysis is asbestos. However, this material was observed to have a toxic and hazardous nature (Zhiyang Peng, 1995).

2.10 Internal Combustion Engines (ICEs)

These refer to the types of engines that burn fuel in a confined chamber. This type of engines is usually used in automobiles and vehicles. These engines use hydrocarbon fuels for their operations. However, their combustion process has been observed to produce a lot of air pollutants as a byproduct (Stone R., 1997). Figure 11 shows a typical drawing of an ICE and its components.

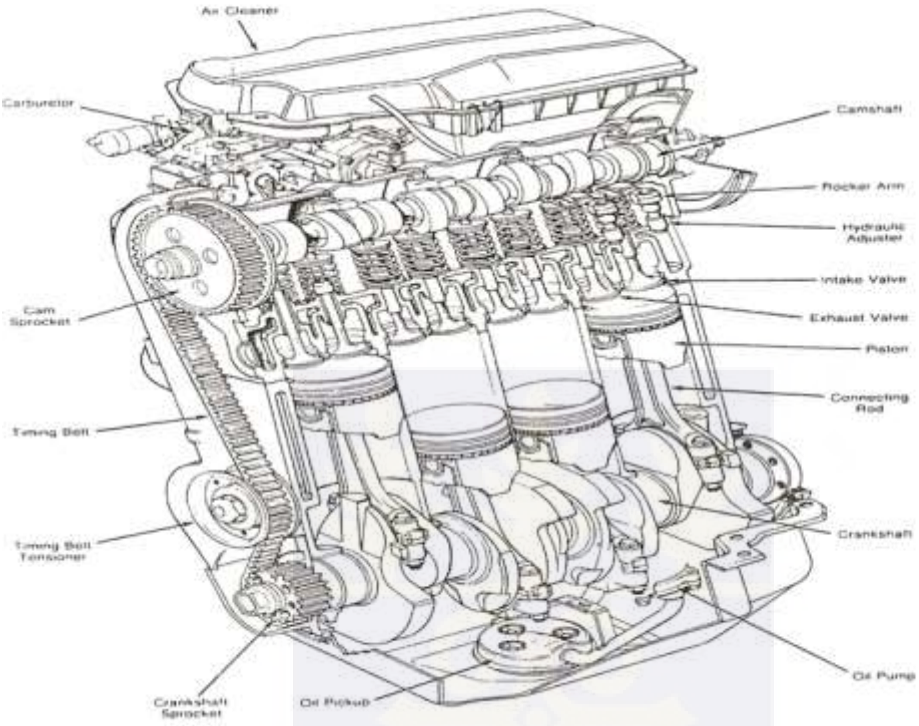


Figure 11: A typical ICE and its components (Heywood and John. B, 1998)

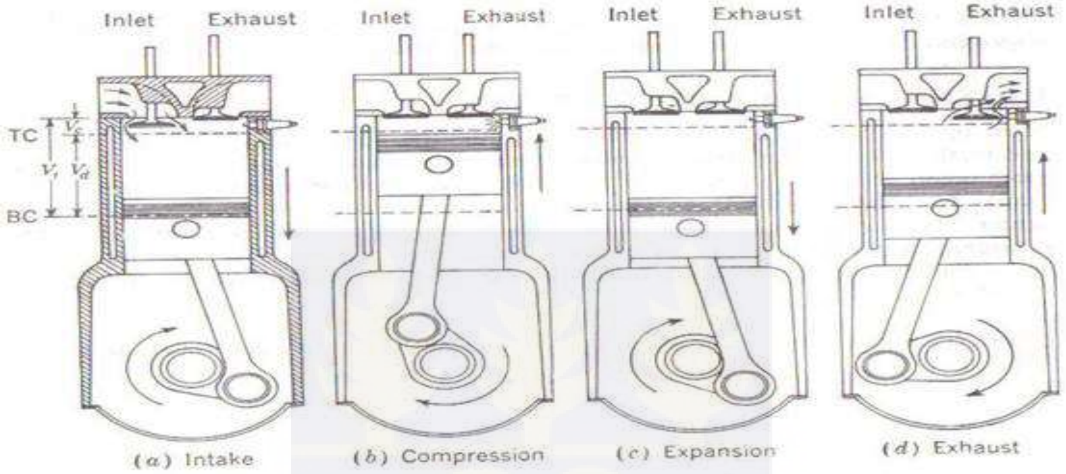
In principle, internal combustion engines can be categorized into the following;

1. Spark Ignition Engines and Compression Ignition Engines
2. Four stroke and Two stroke Engines
3. Reciprocating and Rotary Engines

Typical examples of these categories are briefly described below.

2.10.1 Petrol engines

This is a type of spark ignition engine. The main fuel source for these engines is petrol. Ignition of the fuel- air mixture is done using a spark. Spark-ignition engines can be either two-stroke or four-stroke and are commonly referred to as gasoline engines (Stone R., 1997). During operation of the engine, a mixture of fuel and air is drawn into the cylinder through the intake (inlet) port. The intake (inlet) valve (or valves) then close(s) and the fuel-air mixture gets compressed.



(a) Intake (b) Compression (c) Expansion (d) Exhaust

Figure 12: Petrol engine

The air-fuel mixture is then ignited, using a spark plug. The expansion of burning gases then forces the piston downward for the third stroke (power) and the fourth and final stroke (exhaust) evacuates the spent exhaust gases from the cylinder past the open exhaust valve through the exhaust port to the atmosphere (Stone R., 1997).

2.10.2 Diesel engines

Diesel engines are types of compression ignition engines. In this type of engine, the fuel is ignited solely by the high temperature created by compression of the air-fuel mixture instead of ignition. The engine operates using the diesel cycle. This type of engines uses electrical means to heat the fuel filter and fuel lines (Stone R., 1997). Another alternative method is by using small electric heaters called glow plugs inside the cylinder to warm the cylinders prior to starting. A typical diagram of a diesel engine is shown below.

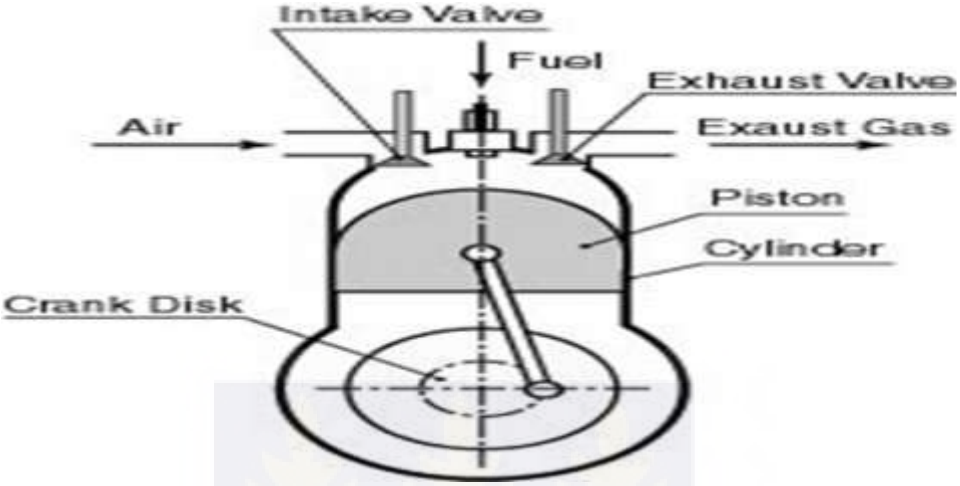


Figure 13: Diagram of a diesel engine

2.10.3 Wankel rotary engines

This type of internal combustion engines uses a rotor. Here, the fuel reacts with an oxidizer to produce gases of high temperature and pressure. This type of engine is characterized by its poor fuel efficiency and exhaust emissions (Stone R., 1997). A typical drawing is indicated below.

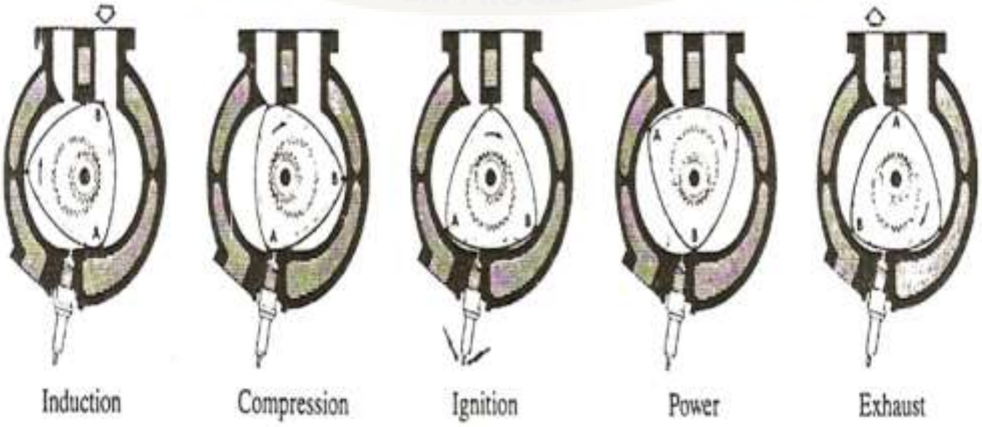
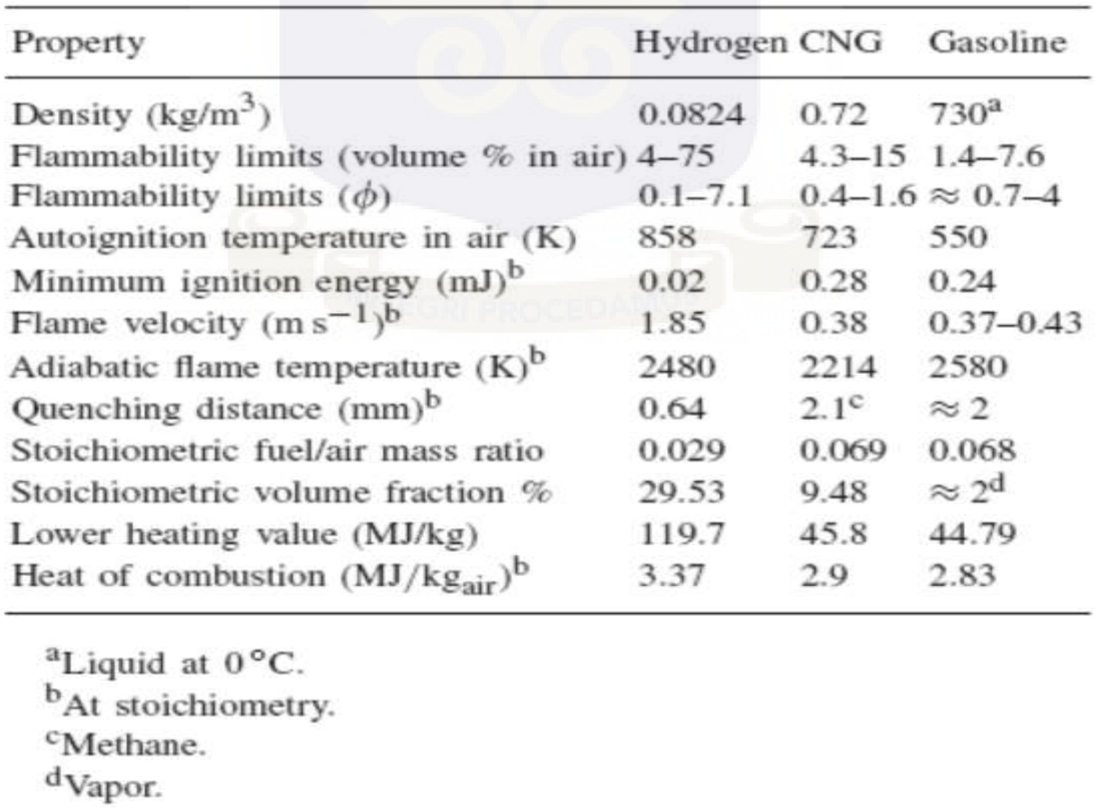


Figure 14: Wankel engine operating cycle

2.10.4 Gas turbine

Gas turbine engines extract energy from a flow of combustion gas. The Energy from the engine is released when the fuel -air mixture is ignited in the combustor. The gases that result are then directed over the blades of the turbines (Stone R., 1997). The gas further spins the turbine and the compressor, and then through a nozzle, to generate additional thrust. This is done by accelerating the hot exhaust gases by expansion back to atmospheric pressure. This type of engine is efficient up to 60% when the waste heat from the gas turbine is recovered using a combined cycle configuration. This application is usually done in the thermal generation. It is technically called cogeneration. The table below compares the properties of various fuels used in internal combustion engines.

Table 3: Fuel properties at 25 °C and 1 atmosphere (Stone R., 1997)



Property	Hydrogen	CNG	Gasoline
Density (kg/m^3)	0.0824	0.72	730[a]
Flammability limits (volume % in air)	4–75	4.3–15	1.4–7.6
Flammability limits (ϕ)	0.1–7.1	0.4–1.6	≈ 0.7–4
Autoignition temperature in air (K)	858	723	550
Minimum ignition energy (mJ)[b]	0.02	0.28	0.24
Flame velocity ($m\,s^{-1}$)[b]	1.85	0.38	0.37–0.43
Adiabatic flame temperature (K)[b]	2480	2214	2580
Quenching distance (mm)[b]	0.64	2.1[c]	≈ 2
Stoichiometric fuel/air mass ratio	0.029	0.069	0.068
Stoichiometric volume fraction %	29.53	9.48	≈ 2[d]
Lower heating value (MJ/kg)	119.7	45.8	44.79
Heat of combustion (MJ/kg_{air})[b]	3.37	2.9	2.83

[a] Liquid at 0 °C.

[b] At stoichiometry.

[c] Methane.

[d] Vapor.

Desirable Characteristics of Good Internal Combustion Engine Fuel

The desirable characteristics of ICE fuels include;

a) High energy content per unit quantity of fuel.

b) Good combustion properties.

c) Availability in large quantities economically.

d) Free from fire hazards.

e) High stability with changes in temperature.

f) Low pollution

g) Easy to store & transport.

h) Products of combustion in gaseous form and non-corrosive.

Methods of rating conventional fuels

Conventional fuels are rated based on their octane and cetane numbers. The octane number of a fuel is important because it describes how well the fuel would ignite under specified conditions. Isooctane and n-heptane are two standard fuels used to compare and rate fuels produced for engine applications. Isooctane and n-heptane have an assigned octane numbers of 100 and 0 respectively.

The cetane number (CN) is, however, a quantifiable number that also indicates whether a fuel will self-ignite early or late. The higher the CN the shorter the ignition delay. The fuels used for cetane number testing include n-cetane (hexadecane), and heptamethyl-nonane (HMN). Both n-cetane and heptamethyl-nonane are accorded cetane numbers of 100 and 15. The cetane number of any fuel can be calculated using the equation below.

$$\text{CN} = (\text{percent of n-cetane}) + (0.15)\,(\text{percent of HMN}) \qquad (50)$$

It is known that the higher the octane number or cetane number of a fuel, the less likely it will self-ignite. This is illustrated the figure 15 below.

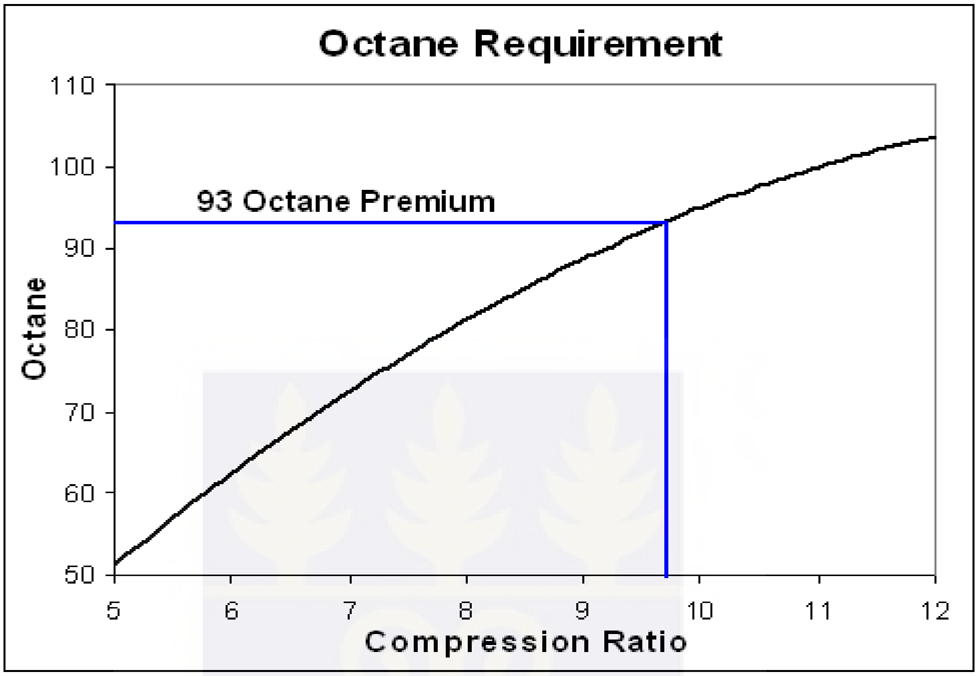


*Figure 15: **Relationship between compression ratio and octane number of fuels***

Conventional Fuel Additives

The skeletal structure of any conventional fuel gives an information of its octane or cetane number. Branched and ring component fuels have higher octane numbers as compared to straight chain component fuels. Because most fuels produced by refineries have low octane number, it has become imperative to improve upon the chemical properties of such fuels. One technique is the addition of additives. One of such additives is tetraethyl lead (TEL). TEL is considered harmful to human contact and hence the mixing process is done by a specialist at refineries and key fuel depots to prevent eventualities.

2.11 Applications of Oxy-hydrogen Gas

High-Efficiency Combustion

Oxyhydrogen gas also known as brown gas has a major influence in the area of combustion. In incineration, oxyhydrogen has been known to increase combustion when sprayed on the waste being burned. This is applicable because oxyhydrogen gas has additional oxygen inherent in its structure to support combustion. When this is done, major air pollutants such as NO_x, CO, SO_x and particulate matter as well as unburnt total hydrocarbons (THC) are immensely reduced. Notably, thermal generation and transportation sectors are also employing this method to enhance their combustion activities. This technology is currently been used in China and Germany.

Applications in Agriculture

Oxyhydrogen gas technology has also been used in the agricultural sector for pickling of fresh foods at the field. This technique is employed in a vacuum pack, enhancing the foods preservation and pest infestation destruction. Oxyhydrogen is further used to provide a drying system where water from foods is removed without any adverse effect on the quality of the food. This does not only enable foods to be stored but also to distribute fresh foods over a longer distance since most of these are perishable foods. This method is currently, been used for preservation of tobacco and orchard growing in Australia.

Cutting and Welding

Oxyhydrogen is one of the finest gases used in the early days for cutting and welding plates and other industrial materials due to its unique characteristics. With the imperforation of other gases such as oxy-acetylene gas, the commercial use of brown gas is low. However, brown gas is still used in some industries for minor works.

Treatment of Nuclear Waste Water

Oxyhydrogen gas is observed to have a major effect on radioactive substances contained in nuclear waste water. Oxyhydrogen gas is shown to have a transmutation characteristics which when blown through contaminated nuclear wastes water, reduce the exposure dose level. This is attributed to the fact that the oxyhydrogen gas trans-mutate the radioisotopes in the water to their inactive forms. This technology is still under developmental stage.

CHAPTER 3

METHODOLOGY

This chapter deals with the construction of an HHO generator. In this chapter, the main principle of HHO generator with materials and components used for construction and the description of the whole construction process are described. Several measurements aimed to evaluate the study of the conditions of an HHO gas production were also realized.

3.1 Materials and Equipment

3.1.1 Materials

All materials used for this practical work was purchased locally at Madina and the Mankoase roundabout at Tema. These include; stainless steel (SS 316) plate, brass bolts and nuts, washers, rubber water holes, torch, acetylene gas arrester, potassium hydroxide (KOH), sodium hydroxide (NaOH), sodium bicarbonate ($NaHCO_3$), distilled water, storage tank, lighter, metal clips, silicon, rubber gasket, epoxy, measuring cylinder, retort stand and source of power.

3.1.2 Equipment

Equipment used for this practical include a rectifier, a 125cc haojue engine, and an E8500 stack gas analyser.

3.2 Procedure

3.2.1 Construction of Electrolyser

Stainless steel plate of thickness 20 gauge was selected for this experiment among platinum and nickel based on economic analysis. 130 square plates consisted of 30 electrodes and 100 neutral plates of dimensions 10 cm x 10 cm were cut out of a Stainless steel grade 316 plate. Two liquid level equalization holes each of radius 3 mm were drilled in each of the 130 plates for passage of electrolyte and Brown's gas. Circular gaskets (125) of radius 5 cm was cut out of an Ethylene Propylene Diene Monomer (EPDM) rubber of thickness 1.6 mm and was fitted between two adjacent electrodes. Two 12 cm x 12 cm x 1.2 cm high transparency acrylic sheets were cut and each fitted with one 90° Anderson Metal Brass Hose Fitting (0.5 in Barb x 0.5 in Male Pipe).

The acrylic sheets (each fitted with two Anderson Metal Brass Fittings) was placed behind each of the external electrodes and tightened with brass bolts, nuts and washers. A bubbler (fitted with 2 Anderson Metal Fittings) and a reservoir tank (fitted with 3 Anderson Metal Fittings) were positioned at a height of 40 cm above the fabricated dry cell oxyhydrogen generator. Finally, the fitted Anderson Elbows on the acrylic sheets and the reservoir tank were connected using a braided PVC hose with inside and outside diameter of 0.25 in and 0.5 in respectively. Some of the electrode plates and neutral plates used are shown below.

Figure 16: Stainless steel neutral plates fitted with PVC gaskets

Figure 17: Stainless Steel electrode plates fitted with PVC gaskets

The fabricated electrolyzer is shown in figure 18 below.

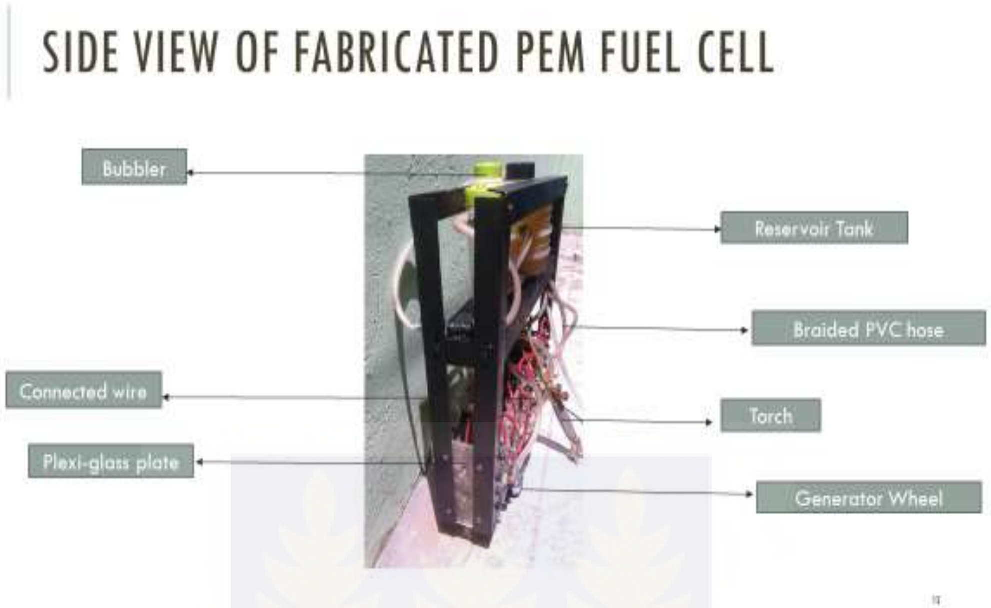


Figure 18: ***The fabricated HHO Generator***

3.2.2 Operation of the Electrolyser

2 L of 0.01 M KOH was placed in the reservoir tank of the HHO gas generator. The solution was allowed to settle in the HHO gas generator for 2 minutes. After the 2 minutes, the switch from the main 220V power source was put on and the rectifier was altered to 9 V. The passage of current was observed to split the water inside the HHO gas generator into hydrogen gas and oxygen gas at the cathode and anode respectively. The hydrogen gas and the oxygen gas together with some amount of electrolyte was collected from the HHO gas generator via a ½ inch pipe hose into the reservoir tank. The continuous recycling of the HHO gas/electrolyte mixture through the HHO gas generator resulted in a pressure build-up inside the reservoir tank. This pressure caused the HHO gas contained in the reservoir tank to flow through an upper vent on the reservoir tank to an auxiliary bubbler ½ filled with distilled water.

The accumulation of HHO gas in the auxiliary bubbler caused the distilled water inside it to be displaced through an attached hose into a graduated measuring cylinder. The volume of distilled water that flowed into the measuring cylinder was recorded as an equivalent amount of HHO gas produced every 10 seconds for five consecutive readings. After the

50 seconds, the inlets of the bubbler and the reservoir tank was opened to allow excess HHO gas to escape the system. After 5 minutes, the covers of the bubbler and reservoir tank was closed and the 0.010 M KOH solution inside the HHO generator was run again at 10 V, 11 V, 12 V, and 13 V respectively and the volumes of HHO gas produced were measured using the water displacement technique. The procedure was again repeated for four other concentrations of KOH (Table 4). The entire procedure was systematically repeated for other prepared concentrations of NaOH and $NaHCO_3$ as described earlier on following the methods used by (A.L. Yuvaraj and D. Santhanaraj, 2012; Noor Alam and K.M. Pandey, 2017; Mohammad Nazry Bin Rosley et al., 2015). Figure 19 shows the set-up for the experiment.

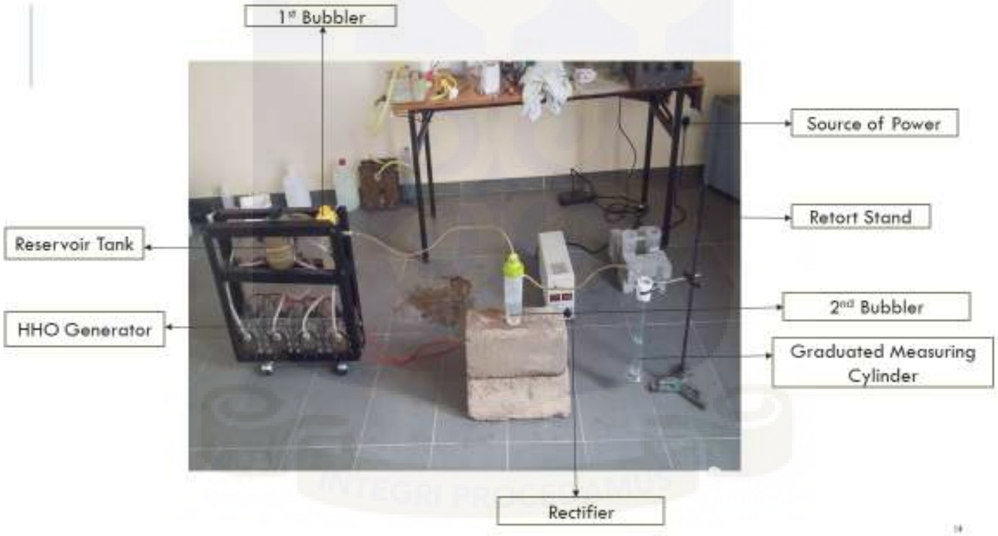


Figure 19. Experimental Setup for HHO gas production and measurement

The quantities of electrolyte used for each experiment is shown in Table 4.

Table 4: **Mass of KOH, NaOH and $NaHCO_3$ weighed for solution preparation**

	Mass of electrolyte (g)		
Strength (mol/dm^3)	**NaOH**	**KOH**	**$NaHCO_3$**
0.010	0.8	1.12	1.68
0.015	1.6	2.24	3.36
0.020	2.4	3.36	5.04
0.025	3.2	4.48	6.72
0.030	4.0	5.60	8.40

Engine test

This experiment was divided into three parts;

1. Running of the motorcycle with only gasoline without HHO gas
2. Running of the motorcycle with gasoline and HHO gas
3. Running of the motorcycle with only HHO gas.

The third option was, however, beyond the focus of the present work.

Emission Test Procedure

The fuel tank of the 125 cubic centimeters, 4-stroke, single cylinder and the air-cooled haojue engine was filled with petrol and the engine was switched on allowing the air intake manifold of the engine to draw only air so that the fuel being burnt in the engine was a mixture of petrol and air only. The engine was allowed to equilibrate for a minimum period of 10 minutes. The E8500 Plus gas analyzer was also switched on and allowed to equilibrate for a period of 10 minutes.

After allowing the gas analyzer to equilibrate, the probe of the gas analyzer was placed just at the end of the exhaust pipe and the concentrations of the emitting gases from the combustion chamber of the engine was measured for a period of 10 minutes.

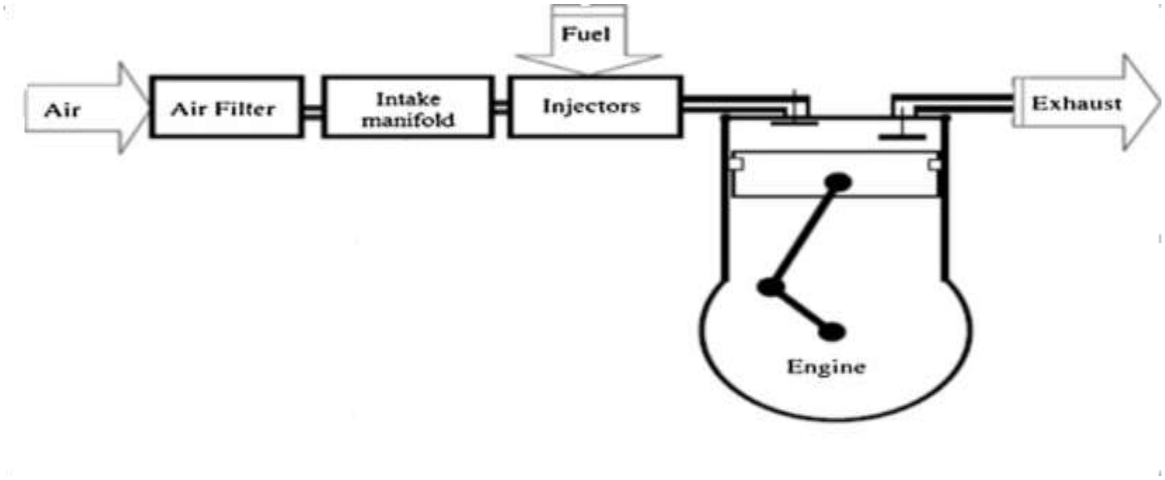


Figure 20.Flow diagram of the experiment using petrol and air mixture as fuel

The procedure was repeated this time, connecting the tube through which the HHO gas runs in the oxyhydrogen electrolyzer to the air intake manifold of the engine via a flow rate meter delivering HHO gas at a rate of 1.2 LPM; so that the fuel being burnt in the combustion chamber of the engine was a mixture of petrol, air and HHO gas only; and the concentrations of the emitting gases was measured as described early on following the methods used by (Premkartikkumar *et al*., 2014; Ahmed H. Sakhrieh *et al*., 2017).

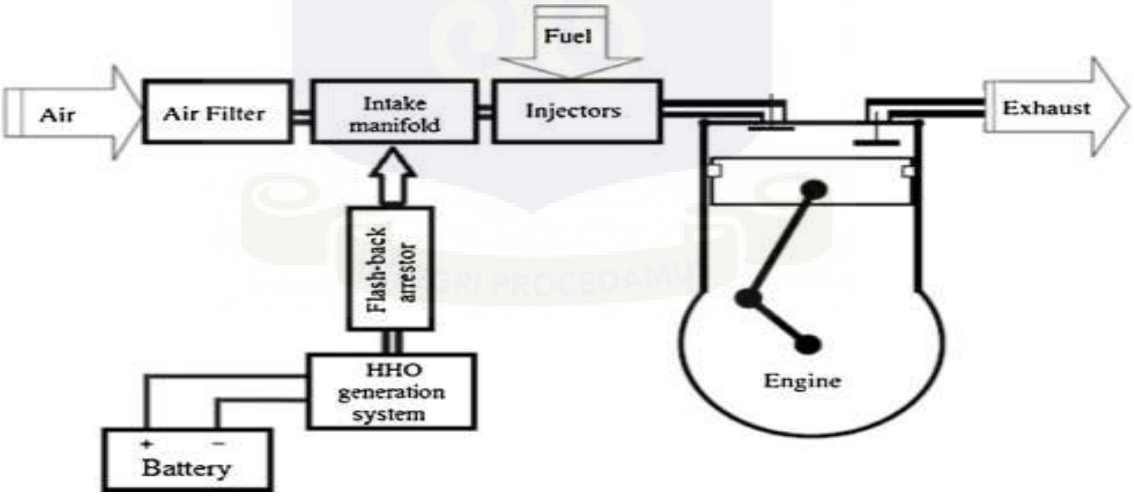


Figure 21. Flow diagram of the experiment using petrol, HHO gas and air mixture as fuel

Table 5. Technical specification of the test engine

Name	Haojue
Type	4-Stroke, Single Cylinder, Air-Cooled
Displacement	125
Maximum Power	5.0 KW @ 7,500 rpm (Maximum Power Converter)
Maximum Torque	8.0 Nm@4,500 rpm (Maximum Power Converter)
Bore x Stroke	52.4 x 49.5
Cooling	Air cooled
Starting Method	Electric & Kick Start
Ignition Type	DC-CDI
Oil Grade	20W50
Gears	4
Clutch	Wet, Multi-Plate Type
Fuel Tank Capacity	4.2 Liters

Table 6.Specification of HHO gas electrolyzer used

Length	12 cm
Width, Height	12 cm, 10 cm
Number of plates	130 316 Stainless steel
Number of gaskets	125 Ethylene Propylene Diene Monomer (EPDM

Table 7. Specification of rectifier used

Length	20cm
Width, Height	10 cm, 14 cm
Rated voltage	0 V-16 V
Rated current	0 A-13 A
Incorporated safety device	Breaker

3.3 Calculation

According to Faraday's first law of electrolysis, the mass of a substance deposited on an electrode surface is directly proportional to the amount of current that flows through the system at standard temperature and pressure.

Mathematically, this statement can be expressed to deduce the theoretical volume of oxyhydrogen gas produced during water electrolysis as follow;

Mass of substance (m) is directly proportional to the quantity of current (Q)

This implies $m = Z\,Q$ (51)

, where Z is called the electrochemical equivalent (ECE).

But the ECE $(Z) = (M/Fv)$, (52)

where 'M' is the atomic weight of the substance, v is the valency of the substance and F is the Faraday's constant (which is 96485 C/mol).

Putting (52) into (51) gives $m = (MQ)/(Fv)$ (53)

Therefore, the mole of the substance deposited $(n) = m/M = (Q)/(Fv)$ (54)

Finally, putting (54) into the Universal Gas Equation; $PV = nRT$, gives equation (55) below.

$$V = \frac{R.T.I.t}{F.P.Z} \qquad (55)$$

Where: V = volume of the gas in liters, R = the ideal gas constant = 0.0820577 l*atm/(mol*K), I = current (A), T = temperature (K), t = time (s), F = Faraday's constant = 96485 Coulombs/mol, P = ambient pressure (atm), and z = number of excess electrons (2 for H_2 and 4 for O_2).

Therefore, at STP (Standard Temperature and Pressure) conditions, considering that the electrolyzer used for this experiment was run for one hour at a current of 1 Ampere, then;

T = 0°C = 273 K

p = 1 atm

t = 3600 s

I = 1 A

But total volume of oxyhydrogen gas produced = hydrogen volume + oxygen volume

Using equation 55;

Volume of hydrogen gas produced = [(0.0820577.1.273.3600)/ (96485.1.2)]

= 0.417921

Volume of oxygen gas produced = [(0.0820577.1.273.3600)/ (96485.1.4)]

= 0.208961

Therefore, total volume of oxyhydrogen produced = 0.417921 + 0.208961

= 0.626882

This, therefore, corresponds to 0.627 l / hour / Ampere or 1.594A / l / hour / cell.

For example, in the experiment using 0.03M KOH at a voltage of 13V, current = 9.68A, time = 50 seconds, the volume of HHO gas produced =248cm^3.

HHO flow rate = (Volume of HHO gas)/time

= (248/50) x 3.6 = 17.856 liters per hour

Theoretical volume of HHO gas produced using 20 cells and current of 9.68A at 32°C gives;

Theoretical volume = 0.6271 x 9.68 x 20 x 0.895082= 110.6895 liters per hour

Therefore, Efficiency of HHO production = (Actual HHO gas produced)/ (Theoretical volume of HHO)

= (17.56)/ (110.6895)

= 16.13%

This calculation was done for all volumes measured.

CHAPTER 4

EXPERIMENTAL RESULTS AND DICUSSIONS

4.1 Results

Table 8. Effect of reaction time on HHO gas production

	Volume of HHO gas produced at constant electrolyte strength and voltage		
Time (s)	KOH	NaOH	$NaHCO_3$
10	31.4	28.0	15.7
20	49.3	43.9	18.6
30	66.0	58.1	21.0
40	82.5	73.1	23.0
50	97.1	87.9	25.3

Table 9. Effect of electrolyte strength on HHO gas production

	Volume of HHO gas produced at constant voltage		
Concentration (M)	KOH	NaOH	$NaHCO_3$
0.010	32.8	28.0	11.8
0.015	60.7	43.9	19.1
0.020	60.7	61.3	22.8
0.025	88.8	69.8	25.4
0.030	83.3	74.0	24.5

Table 10.Effect of voltage on HHO gas production

	Volume of HHO gas produced at constant strength		
Voltage (V)	KOH	NaOH	$NaHCO_3$
9	26.8	21.9	11.9
10	34.8	31.6	17.7
11	59.3	56.7	19.9
12	91.7	84.4	25.0
13	113.5	99.3	29.0

Table 11. Engine emission components with and without HHO gas

Emission component	**Petrol +Air**	**Petrol +Air + HHO gas**
SO_2	4,073.40 mg/m^3	86.20 mg/m^3
NO_x	59.80 mg/m^3	50.00 mg/m^3
CO	16,059.40 mg/m^3	5,017.90 mg/m^3
O_2	15.96 %	17.64 %
THCs	3,075.60 ppm	1,991.90 ppm

4.2 Discussion

4.2.1 Effect of time on HHO gas production

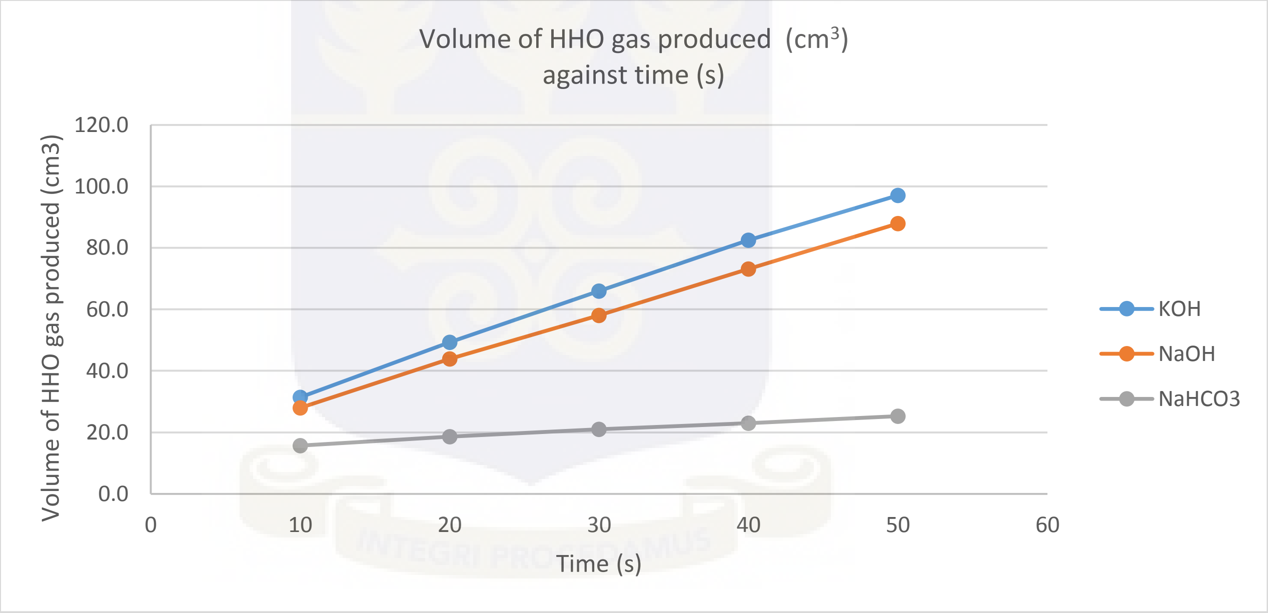


Figure 22. Variation of HHO gas production with time at constant electrolyte concentration and voltage

Table 8 shows that increasing time at constant strength and voltage increased the volume of HHO gas produced. This trend may be attributed to the increased in electrical conductivity associated with the addition of the electrolytes as observed by Noor Alam and

K.M. Pandey, 2017. The results showed 209.24%, 213.93% and 61.15% increase in HHO gas production using KOH, NaOH and $NaHCO_3$ respectively.

4.2.2 Effect of voltage on HHO gas production

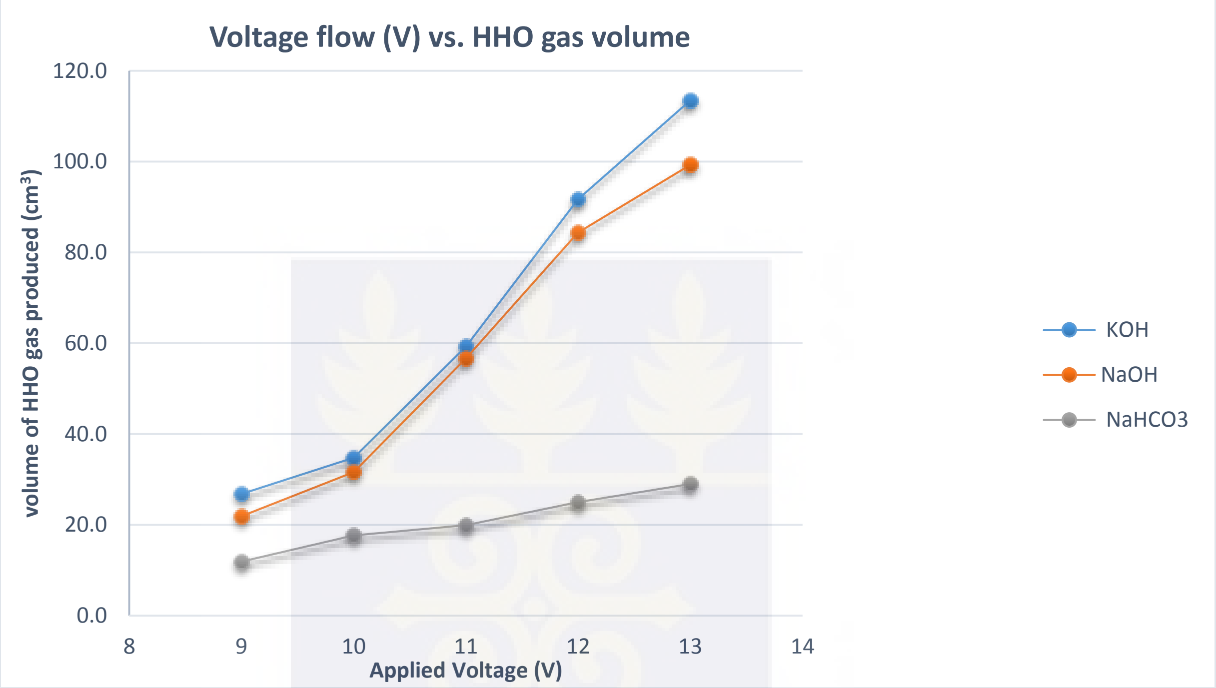


Figure 23. Effect of variation of voltage on the production HHO gas at constant strength and time

Figure 23 shows that, the production of HHO gas gradually increased with increased in voltage flow. This could be attributed to the fact that, increasing voltage uniformly increased the current density on the surface of the HHO gas electrolyser electrodes in accordance with Ohm's law. The increased in current density caused an increase in the number of electrons needed for the reduction of hydrogen ions to hydrogen gas hence facilitated the production of hydrogen gas at the cathode to react with oxygen gas produced at the anode as observed by A.L. Yuvaraj and D. Santhanaraj, 2013. From Table 10, altering the voltage from 9 V to 13 V, showed an increase in HHO gas production by 113.5cm^3, 99.3cm^3 and 29.0 cm^3 when KOH, NaOH and $NaHCO_3$ were used respectively.

4.2.3 Effect of electrolyte strength on HHO gas production

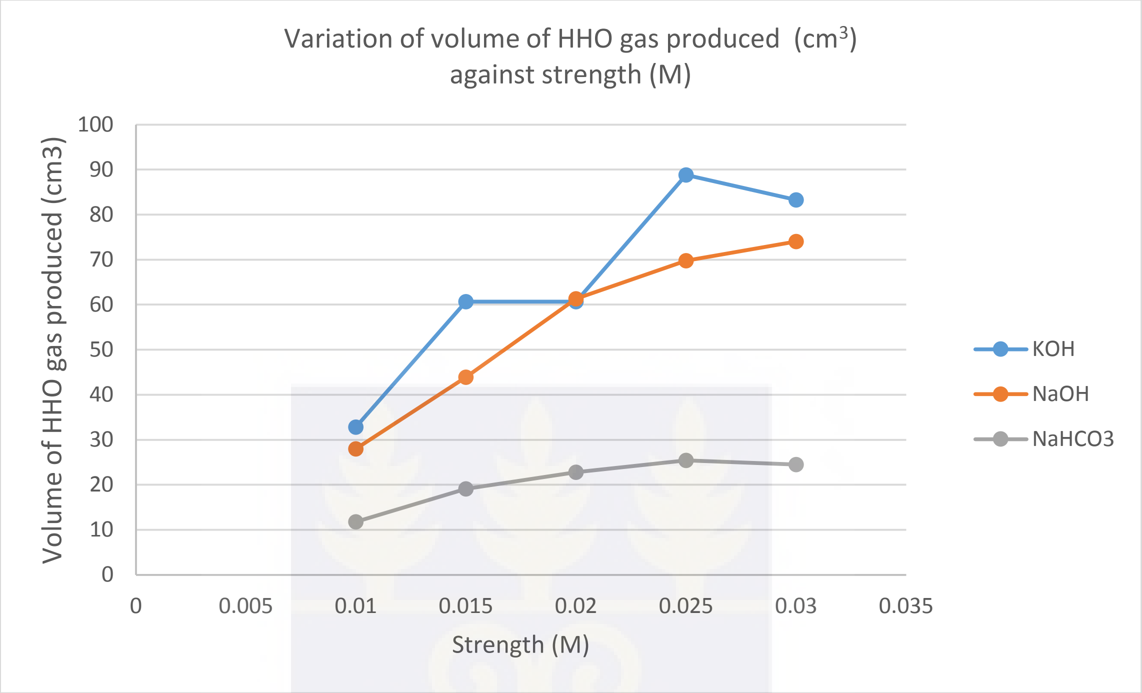


Figure 24. Effect of electrolyte strength on the production of HHO gas at constant voltage and time

Table 9 shows that increasing the strengths of KOH, NaOH and $NaHCO_3$ from 0.010M to 0.030M showed a corresponding increase in the volume of HHO's gas produced by 170.73 %, 164.29 % and 107.63% respectively. The increase in volume of HHO gas as a result of increasing electrolyte strength could be attributed to the increase in ionic conductivity which caused increased in the number of effective ionic collisions per unit time as observed by A.L. Yuvaraj and D. Santhanaraj, 2013.

4.2.4 SO_2 emissions

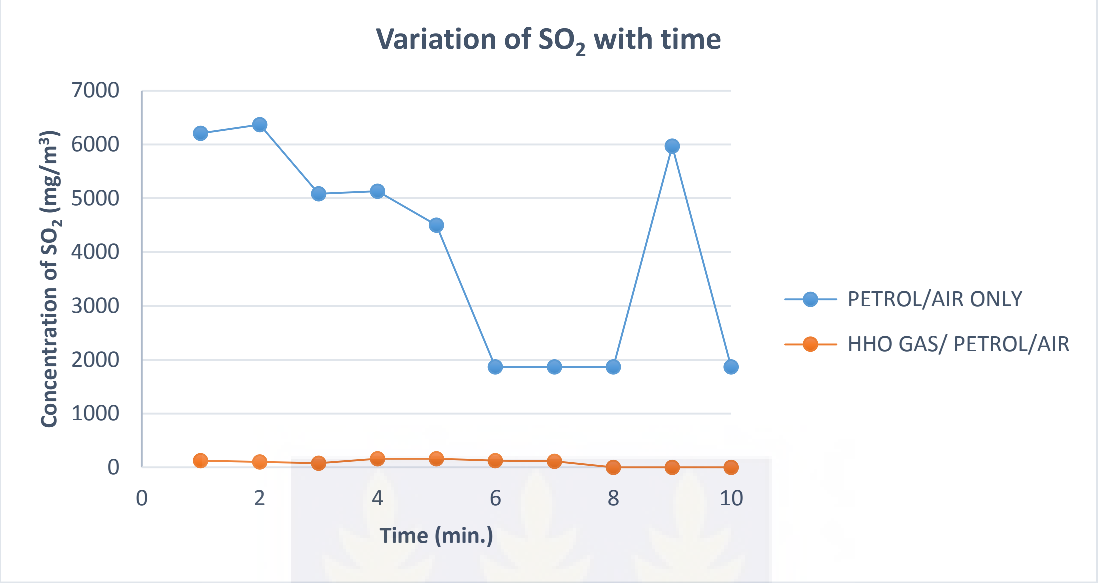


Figure 25. Variation of Sulphur dioxide (SO2) emissions with time

Table 11 shows that the average concentration of SO_2 gas of the emissions resulting from the combustion of petrol/air mixture in the combustion chamber of the test engine was 4,073.40 mg/m^3. With the introduction of the HHO gas into the petrol/air mixture in the combustion chamber, the average concentration of SO_2 gas decreased drastically from 4,073.40 mg/m^3 to 86.20 mg/m^3 representing 97.9% decrease in the concentration of SO_2 gas. The decrease in the concentration of SO_2 gas may be attributed to the fact that when SO_2 gas reacts with oxygen in the HHO gas, the SO_2 gas is converted to SO_3 gas (Lawrence P. Belo et al., 2014). R.W. Fair and B.A. Thrush, 1969 also reported that when hydrogen in the HHO gas reacts with SO_2 gas, there is an efficient heterogeneous reduction of SO_2 gas. These effects may explain the drastic decrease in the concentration of SO_2 gas to almost a constant average value of 86.20 mg/m^3 emitting from the combustion chamber within the measuring period as shown in Figure 25.

4.2.5 NO_x emissions

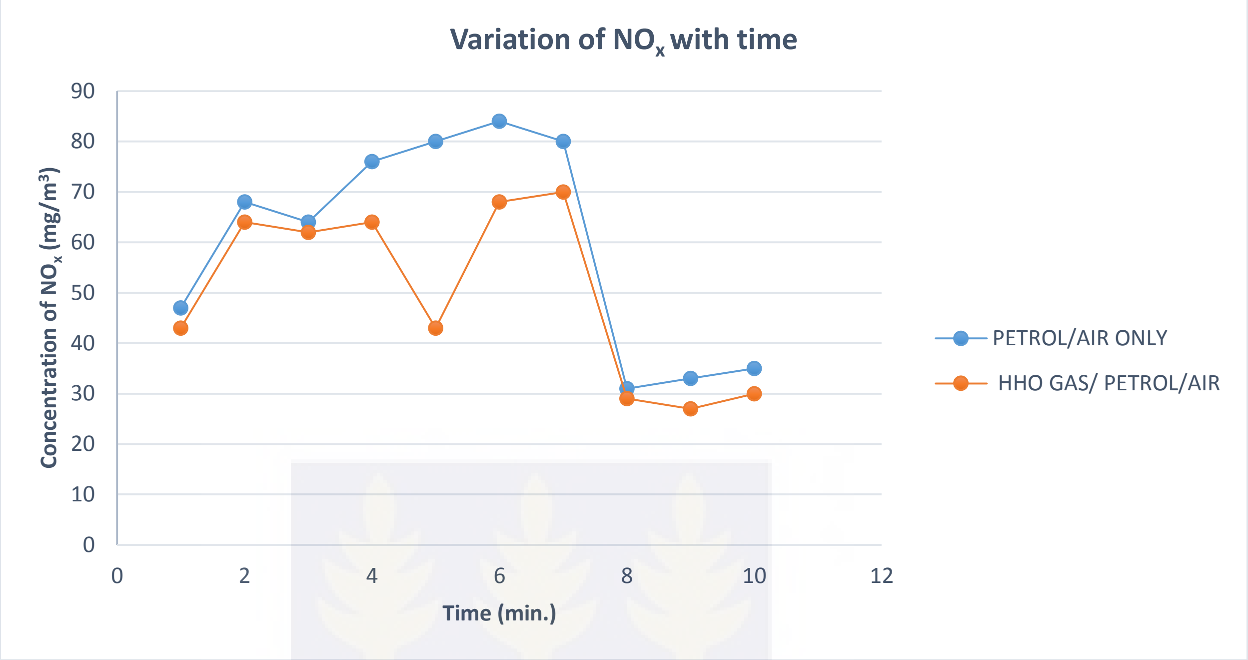


Figure 26. Variation of Oxides of nitrogen (NOx) emission with time

Figure 26 shows that the concentration of NOx gas produced from the petrol/air mixture increased from 47.0 mg/m^3 to 84.0 mg/m^3 at the 6 minute and then dropped to 35.0 mg/m^3 at the 10th minute giving average NOx gas concentration of 59.80 mg/m^3 (Table 11). Similar work carried out by Sa'ed A. Musmar and Ammar A. Al-Rousan, 2011 reported that the concentration of NOx gas increased with temperature of the system with respect to time; this may account for the observed increase in the concentration of NOx gas within the first 6 minutes. With the introduction of the HHO gas into the petrol/air mixture, the average NOx gas concentration decreased to 50.0 mg/m3 (Table 11) representing 16.4% reduction. The decrease in the average concentration of NOx gas could be ascribed to the presence of the HHO gas that reduced the temperature of the system and hence caused unfavorable condition for the formation of NOx as observed by Sa'ed A. Musmar and Ammar A. Al-Rousan, 2011.

4.2.6 CO emissions

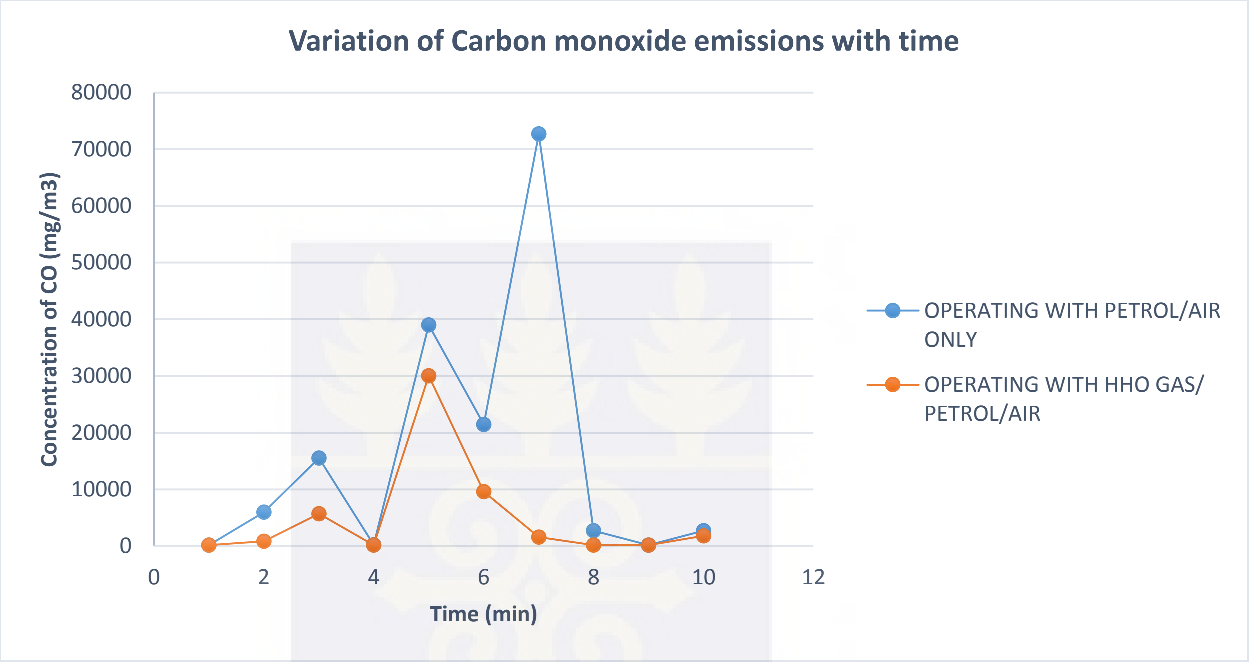


Figure 27. Variation of Carbon monoxide (CO) emissions with time

The percentage reduction in the average concentration of CO was found to be 68.8% (Table 11). The decrease in the average concentration of CO could be that, the introduction of the HHO gas in the petrol/air mixture caused the level of oxygen in the mixture in the combustion chamber to increase leading to an enhancement in the conversion of CO to CO_2 thereby reducing the CO concentration as observed (Bari S. and Mohammad E.M.,2010).

4.2.7 THC emissions

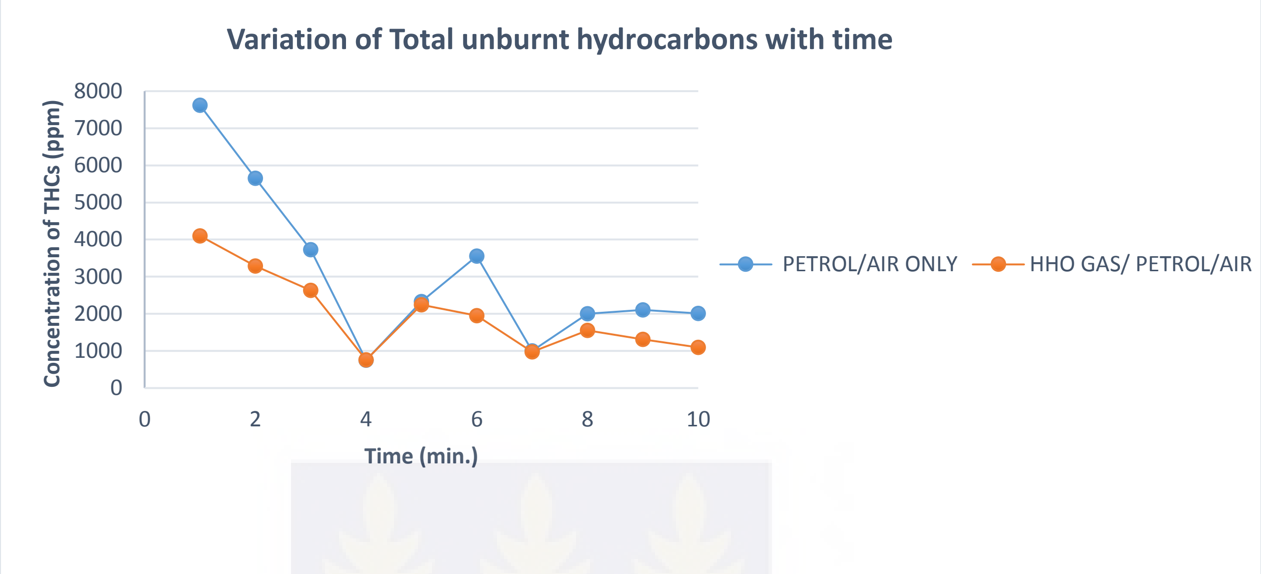


Figure 28. Variation of Total unburnt hydrocarbons (THCs) emissions with time

The variation of the concentrations of Total unburnt Hydrocarbons (THCs) emissions with time is depicted in Figure 28. The average reduction in the concentrations of THCs was found to be 35.2% (Table 11). This reduction in the average concentration of THCs could be attributed to the increase in the concentration of oxygen gas in the combustion chamber due to the presence of the HHO gas causing reasonable decrease in the average concentration of THCs by converting THCs to CO, CO_2, H_2O, and heat energy in line with experiment carried out by Ali Can et al., 2010.

4.2.8 Oxygen (O_2) emissions

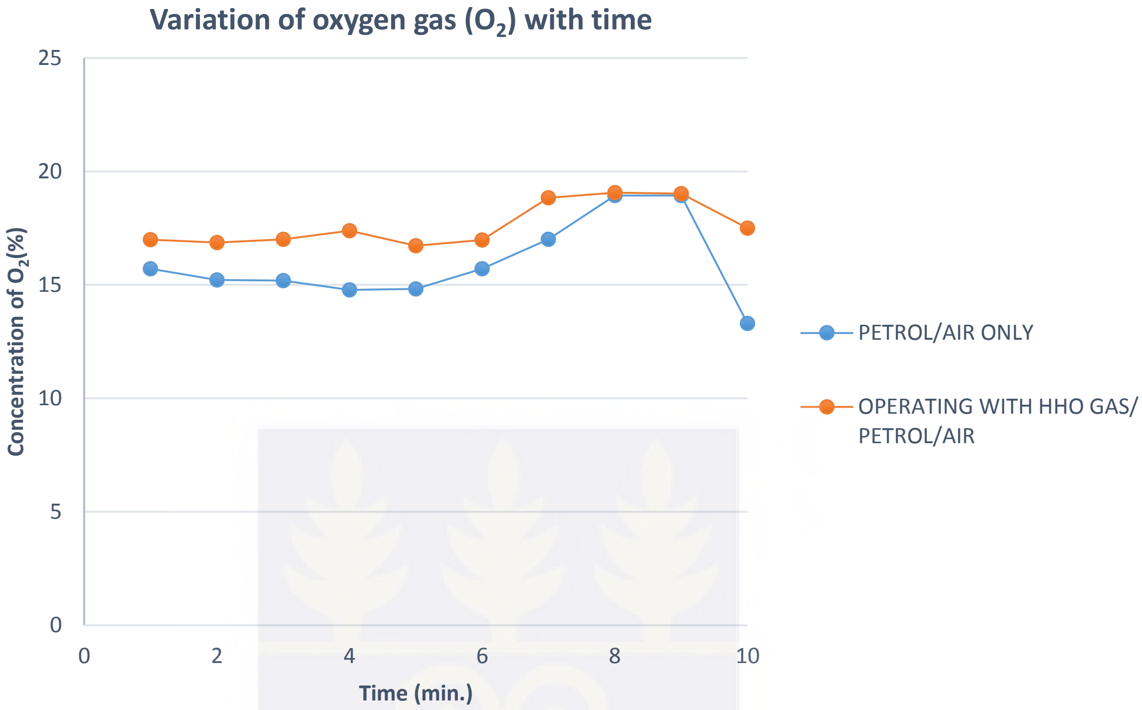


Figure 29. Variation of oxygen gas (O2) emissions with time

Figure 29 above shows that the concentration of oxygen in the HHO/petrol/air mixture in the combustion chamber at any time was higher than the concentration of oxygen in the petrol/air mixture in the combustion chamber. Overall, the average concentration of oxygen gas increased by 1.7% (Table 11). The increase in the average concentration of oxygen gas emitted could be assigned to the presence of oxygen in the HHO gas introduced into the combustion chamber.

CHAPTER 5

5.1 CONCLUSIONS AND RECOMMENDATIONS

5.1.1 Conclusions

1. A Proton Exchange Membrane Fuel Cell consisting of 3 positive plates, 3 negative plates, and 20 neutral plates with surface area of 100 cm^2 was designed and produced using Stainless Steel plate 316 L.

2. The constructed Proton Exchange Membrane Fuel Cell was used to produce Brown's gas using KOH, NaOH, and $NaHCO_3$ by varying the solution strength of the electrolytes and applied voltage from 0.010 M-0.030 M and 9 V-13V respectively. The optimum yield of HHO gas was observed to be 113.5 cm^3 when the HHO generator was run at 2.17 V using 0.025 M KOH for 50 seconds.

3. The Brown's gas produced as an alternative source of fuel was subsequently used to reduce emissions emitted from a 125 cc Haojue engine by injecting the Brown's gas into the air intake manifold to mix with petrol/air mixture in the combustion chamber of the engine.

4. The measurement of gaseous pollutants (CO, NO_x, THCs, and SO_2) emitted from the exhaust of the 125 cc Haojue engine showed that, the average concentrations of Sulphur dioxide (SO_2), Oxides nitrogen (NO_x), Carbon monoxide (CO) and Total unburnt hydrocarbons (THCs) decreased by 97.9%, 16.4%, 68.8% and 35.2% respectively. However, the average concentration of oxygen gas (O_2) increased by 1.7%.

5.1.2 Recommendations

Electrolysis of water is still a developing technology considered as one of the most viable methods of producing pure oxyhydrogen for commercial use. However, to reach this critical point in electrolysis, there is the need to undertake intensive research to understand all the factors that affect and reduces the efficiency of this technology. In connection with this, the following recommendations are proposed for further consideration and investigation.

1. The process of degassing should be employed at the start of every experiment to ensure that no gas is dissolved in the electrolyte solution. This is to reduce electrolyte resistance.

2. Stainless steel plates (SS316) was used for this experiment. It is therefore recommended that a different metal of good conductivity be selected to compare the yield of oxyhydrogen gas.

3. The production of oxyhydrogen gas is affected by the surface area of a given metal electrode. It is therefore recommended that an intensive research be carried out for improvement in this area of study.

4. The volume of oxyhydrogen gas produced in this experiment was measured using the method of water displacement. However, it is believed that the use of a flow rate meter in the large extent will be more helpful since this can eliminate human error to give more accurate result.

5. The evaluation of effect of electrolyte concentration on electrode weight loss in an HHO gas electrolyser is one area scientist are currently researching. I will therefore recommend further studies in this area using different affordable metals.

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APPENDIX: TABLE OF RESULTS

CURRENT AND TIME ON GAS PRODUCED AT DIFFERENT CONCENTRATIONS OF NaOH, KOH, AND $NaHCO_3$

0.01 NaOH

	TIMES				
CURRENT	10S	20S	30S	40S	50S
	GAS PRODUCED (%)				
2.18A	26.00	32.67	42.00	50.00	58.00
2.06A	22.00	31.33	39.33	47.33	55.33
1.72A	20.67	29.33	36.67	43.33	49.33
0.94A	19.33	24.00	26.00	28.67	31.33
0.58A	19.00	20.67	21.67	22.67	23.67
FPr.(C×T)	0.000				
%CV	8.53				

MAIN EFFECT

CURRENT	GAS PRODUCED (%)	TIME	GAS PRODUCED (%)
13V/2.18A	41.73	10S	21.40
12V/2.06A	39.07	20S	27.60
11V/1.72A	35.60	30S	33.13
10V/0.94A	26.13	40S	38.40
9V/0.58A	21.53	50S	43.53
FPr.	0.000		0.000
%CV	8.53		8.53

0.015 NaOH

	TIMES				
CURRENT	10S	20S	30S	40S	50S
	GAS PRODUCED (%)				
6.25A	36.00	70.00	100.67	132.00	162.67
5.27A	36.00	59.33	81.33	106.00	128.67
3.52A	29.33	43.33	58.00	69.33	82.67
1.90A	24.67	30.00	34.00	42.00	45.00
1.09A	22.00	28.00	30.33	32.33	34.00
FPr.	0.000				
%CV	2.66				

CURRENT	GAS PRODUCED (%)	TIME	GAS PRODUCED (%)
6.25A	100.27	10S	29.60
5.27A	82.27	20S	46.13
3.52A	56.53	30S	60.87
1.90A	35.13	40S	76.33
1.09A	29.33	50S	90.60
FPr.	0.000	FPr.	0.000
%CV	2.66	%CV	2.66

			0.02 NaOH		
			TIMES		
CURRENT	10S	20S	30S	40S	50S
			GAS PRODUCED (%)		
6.83A	44.00	74.67	104.00	133.33	163.00
5.36A	36.00	62.00	85.33	109.33	133.33
3.86A	28.67	44.67	60.67	74.00	90.67
2.00A	22.00	28.00	32.00	36.67	42.67
1.24A	18.00	20.00	22.00	25.00	26.67
FPr.	0.000				
%CV	6.82				

MAIN EFFECT

CURRENT	GAS PRODUCED (%)	TIME	GAS PRODUCED (%)
6.83A	103.80	10S	29.73
5.36A	85.20	20S	45.87
3.86A	59.73	30S	60.80
2.00A	32.27	40S	75.67
1.24A	22.33	50S	91.27
FPr.	0.000		0.000
%CV	6.82		6.82

0.025 NaOH					
			TIMES		
CURRENT	10S	20S	30S	40S	50S
			GAS PRODUCED (%)		
9.00A	62.00	118.67	178.00	239.33	246.67
8.91A	47.33	90.67	128.00	166.00	204.67
5.56A	32.00	56.00	74.67	96.00	110.00
2.89A	24.67	33.33	40.00	46.67	53.33
1.72A	29.33	32.67	34.67	36.67	38.00
FPr.	0.000				
%CV	3.93				

MAIN EFFECT

CURRENT	GAS PRODUCED (%)	TIME	GAS PRODUCED (%)
9.00A	168.93	10S	39.07
8.91A	127.33	20S	66.27
5.56A	73.73	30S	91.07
2.89A	39.60	40S	116.93
1.72A	34.27	50S	130.53
FPr.	0.000	FPr.	0.000
%CV	3.93	%CV	3.93

	0.03NaOH				
			TIMES		
CURRENT	10S	20S	30S	40S	50S
			GAS PRODUCED (%)		
9.15A	58.00	108.00	156.00	193.67	249.33
7.49A	50.67	87.33	126.00	161.33	198.00
4.68A	33.33	52.00	71.33	92.00	108.00
2.84A	23.33	32.67	41.33	50.00	57.33
1.72A	20.00	22.67	26.00	29.33	34.67
FPr.	0.000				
%CV	2.54				

MAIN EFFECT

CURRENT	GAS PRODUCED (%)	TIME	GAS PRODUCED (%)
9.15A	153.00	10S	37.07
7.49A	124.67	20S	60.53
4.68A	71.33	30S	84.13
2.84A	40.93	40S	105.27
1.72A	26.53	50S	129.47
FPr.	0.000		0.000
%CV	2.54		2.54

0.01 KOH

	TIMES				
CURRENT	10S	20S	30S	40S	50S
3.74A	29.33	42.67	56.00	70.00	82.00
1.99A	28.00	37.33	45.33	54.67	62.00
1.75A	25.33	34.00	40.00	46.00	52.00
1.12A	20.00	24.00	26.67	29.33	32.00
0.62A	19.33	22.00	23.00	24.00	25.00
FPr.	0.000				
%CV	3.65				

CURRENT	GAS PROD.	TIME	GAS PROD.
3.74A	56.00	10S	24.40
1.99A	45.47	20S	32.00
1.75A	39.47	30S	38.20
1.12A	26.27	40S	44.80
0.62A	22.80	50S	50.60
FPr.	0.000		0.000
%CV	3.65		3.65

0.015 KOH

	TIMES				
CURRENT	10S	20S	30S	40S	50S
4.84A	30.67	53.67	72.67	95.33	113.33
4.21A	29.67	47.33	65.33	82.67	99.33
3.08A	24.67	38.00	48.00	58.67	70.00
1.57A	20.00	27.33	28.00	31.67	37.33
0.80A	20.33	23.33	25.00	27.67	29.33
FPr.	0.000				
%CV	8.01				

MAIN EFFECT

CURRENT	GAS PROD.	TIME	GAS PROD.
4.84A	73.13	10S	25.00
4.21A	64.80	20S	37.33
3.08A	47.87	30S	47.80
1.57A	28.27	40S	59.20
0.80A	25.13	50S	69.87
FPr.	0.000		0.000
%CV	8.01		8.01

0.02 KOH

	TIMES				
CURRENT	10S	20S	30S	40S	50S
6.71A	39.33	73.33	102.67	135.33	165.33
5.58A	36.00	62.67	85.33	108.00	132.00
3.71A	29.33	47.33	58.67	71.33	85.33
2.20A	25.33	32.00	38.67	45.33	51.33
1.03A	18.67	20.67	21.67	22.67	23.67
FPr.	0.000				
%CV	5.71				

MAIN EFFECT

CURRENT	GAS PROD.	TIME	GAS PROD.
6.71A	103.20	10S	29.73
5.58A	84.80	20S	47.20
3.71A	58.40	30S	61.40
2.20A	38.53	40S	76.53
1.03A	21.47	50S	91.53
FPr.	0.000		0.000
%CV	5.71		5.71

0.025 KOH

	TIMES				
CURRENT	10S	20S	30S	40S	50S
8.71A	42.67	87.33	126.00	165.33	210.00
7.31A	35.33	70.00	100.00	133.33	166.67
5.03A	31.33	53.33	70.67	90.00	107.33

2.63A	20.00	26.33	32.67	40.00	46.00
1.21A	14.67	17.33	18.67	19.67	21.33
FPr.	0.000				
%CV	6.89				

MAIN EFFECT

CURRENT	GAS PROD.	TIME	GAS PROD.
8.71A	126.27	10S	28.80
7.31A	101.07	20S	50.87
5.03A	70.53	30S	69.60
2.63A	33.00	40S	89.67
1.21A	18.33	50S	110.27
FPr.	0.000		0.000
%CV	6.89		6.89

0.03 KOH

	TIMES				
CURRENT	10S	20S	30S	40S	50S
9.68A	56.67	90.00	136.67	181.33	225.33
8.39A	38.00	74.00	110.00	146.00	185.33
5.08A	28.00	49.33	67.33	87.33	105.33
2.53A	19.33	26.00	32.67	38.00	44.00
1.40A	18.00	20.00	22.00	24.00	26.00
FPr.	0.000				
%CV	3.98				

MAIN EFFECT

CURRENT	GAS PROD.	TIME	GAS PROD.
9.68A	138.00	10S	32.00
8.39A	110.67	20S	51.87
5.08A	67.47	30S	73.73
2.53A	32.00	40S	95.33
1.40A	22.00	50S	117.20
FPr.	0.000		0.000
%CV	3.98		3.98

0.01 NaHCO3					
			TIMES		
CURRENT	10S	20S	30S	40S	50S
0.77A	14.67	18.67	20.33	22.00	24.00
0.61A	14.67	18.00	20.00	21.67	23.33
0.41A	15.67	17.67	20.00	21.67	23.00
0.26A	0.00	0.00	0.00	0.00	0.00
0.22A	0.00	0.00	0.00	0.00	0.00
FPr.	0.000				
%CV	4.15				

MAIN EFFECT

CURRENT	GAS PROD.	TIME	GAS PROD.
0.77A	19.99	10S	9.00
0.61A	19.53	20S	10.87
0.41A	19.60	30S	12.07
0.26A	0.00	40S	13.07
0.22A	0.00	50S	14.07
FPr.	0.000		0.000
%CV	4.15		4.15

0.015 NaHCO3					
			TIMES		
CURRENT	10S	20S	30S	40S	50S
1.39A	20.00	26.66	32.00	36.00	40.00
0.79A	19.67	23.33	27.33	28.33	30.33
0.61A	14.33	17.33	18.67	20.33	22.00
0.49A	17.67	19.67	20.67	20.67	21.33
0.31A	0.00	0.00	0.00	0.00	0.00
FPr.	0.000				
%CV	7.42				

MAIN EFFECT

CURRENT	GAS PROD.	TIME	GAS PROD.
1.39A	30.93	10S	14.33
0.79A	25.80	20S	17.40
0.61A	20.13	30S	19.73
0.49A	18.40	40S	21.07
0.31A	0.00	50S	22.73
FPr.	0.000		0.000
%CV	7.42		7.42

	0.02 NaHCO3				
			TIMES		
CURRENT	10S	20S	30S	40S	50S
1.45A	16.67	22.00	26.67	32.67	37.33
1.09A	17.33	20.67	22.67	27.67	31.33
0.73A	15.67	17.67	19.00	20.67	22.00
0.58A	16.67	20.33	21.33	22.33	23.33
0.43A	21.00	22.33	23.33	24.00	24.67
FPr.	0.000				
%CV	4.94				

MAIN EFFECT

CURRENT	GAS PROD.	TIME	GAS PROD.
1.45A	27.07	10S	17.47
1.09A	23.93	20S	20.60
0.73A	23.07	30S	22.60
0.58A	20.80	40S	25.47
0.43A	19.00	50S	27.73
FPr.	0		0
%CV	4.94		4.94

0.025 NaHCO3

			TIMES		
CURRENT	10S	20S	30S	40S	50S
1.79A	20.67	26.00	35.33	40.67	47.33
1.34A	18.00	23.33	27.33	32.67	37.33
0.82A	17.33	18.33	21.00	22.00	23.67
0.61A	21.33	23.33	25.00	25.33	26.00
0.56A	20.00	20.00	19.33	21.67	22.00
FPr.	0.000				
%CV	4.75				

MAIN EFFECT

CURRENT	GAS PROD.	TIME	GAS PROD.
1.79A	34.00	10S	19.47
1.34A	27.72	20S	22.20
0.82A	24.20	30S	25.60
0.61A	21.00	40S	28.47
0.56A	20.07	50S	31.27
FPr.	0.000		0.000
%CV	4.75		4.75

0.03 NaHCO3

			TIMES		
CURRENT	10S	20S	30S	40S	50S
1.96A	20.00	27.33	34.00	39.33	45.33
1.37A	19.33	25.33	28.67	31.33	35.33
0.86A	18.67	20.33	22.00	23.67	28.00
0.65A	20.00	21.33	24.00	24.33	26.00
0.52A	12.67	14.67	16.00	16.33	18.00
FPr.	0.000				
%CV	5.25				

MAIN EFFECT

CURRENT	GAS PROD.	TIME	GAS PROD.
1.96A	33.20	10S	18.13
1.37A	28.00	20S	21.80
0.86A	23.13	30S	24.93
0.65A	22.53	40S	27.00
0.52A	15.53	50S	30.53
FPr.	0.000	FPr.	0.000
%CV	5.25	%CV	5.25

KOH

INTERACTION EFFECT OF VOLTAGE, TIME AND KOH ON GAS PRODUCTION

		KOH				
VOLTAGE	TIME	0.01M	0.015M	0.02M	0.025M	0.03M
13V	10S	26.0	36.0	44.0	62.0	58.0
	20S	32.7	70.0	74.7	118.7	108.0
	30S	42.0	100.7	104.0	178.0	156.0
	40S	50.0	132.0	133.3	239.3	193.7
	50S	58.0	162.7	163.0	246.7	249.3
12V	10S	22.0	36.0	36.0	47.3	50.7
	20S	31.3	59.3	62.0	90.7	87.3
	30S	39.3	81.3	85.3	128.0	126.0
	40S	47.3	106.0	109.3	166.0	161.3
	50S	55.3	128.7	133.3	204.7	198.0
11V	10S	20.7	29.3	28.7	32.0	33.3
	20S	29.3	43.3	44.7	56.0	52.0
	30S	36.7	58.0	60.7	74.7	71.3
	40S	43.3	69.3	74.0	96.0	92.0
	50S	49.3	82.7	90.7 C	110.0	108.0
10V	10S	19.3	24.7	22.0	24.7	23.3
	20S	24.0	30.0	28.0	33.3	32.7
	30S	26.0	34.0	32.0	40.0	41.3
	40S	28.7	42.0	36.7	46.7	50.0
	50S	31.3	45.0	42.7	53.3	57.3
	10S	19.0	22.0	18.0	29.3	20.0

9V	20S	20.7	28.0	20.0	32.3	22.7
	30S	21.7	30.3	22.0	34.7	26.0
	40S	22.7	32.3	25.0	36.7	29.3
	50S	23.7	34.0	26.7	38.0	34.7
FPr. (V×T×N)		0.000				
%CV		4.56				

INTERACTION EFFECT OF VOLTAGE AND TIME ON GAS PRODUCTION

	TIME				
VOLTAGE	10S	20S	30S	40S	50S
13V	45.2	80.8	116.1	149.7	175.9
12V	38.4	66.1	92.0	118.0	144.0
11V	28.5	45.1	60.3	74.9	88.1
10V	23.1	29.6	34.7	40.8	45.9
9V	21.7	24.8	26.9	29.2	31.4
FPr. (V×T)	0				
%CV	4.56				

INTERACTION EFFECT OF VOLTAGE AND KOH ON GAS PRODUCTION

	KOH				
VOLTAGE	0.01M	0.015M	0.02M	0.025M	0.03M
13V	41.7	100.3	103.8	168.9	153.0
12V	39.1	82.3	85.2	127.3	124.7
11V	35.6	56.5	59.7	73.7	71.3
10V	26.1	35.1	32.3	39.6	40.9
9V	21.5	29.3	22.3	34.3	26.5
FPr. (V×N)	0				
%CV	4.56				

INTERACTION EFFECT OF TIME AND KOH ON GAS PRODUCTION

	KOH				
TIME	0.01M	0.015M	0.02M	0.025M	0.03M
10S	21.4	29.6	29.7	39.1	37.1
20S	27.6	46.1	45.9	66.3	60.5
30S	33.1	60.9	60.8	91.1	84.1
40S	38.4	76.3	75.6	116.9	105.3
50S	43.5	90.6	91.3	130.5	129.5
FPr. (T×N)	0				
%CV	4.56				

MAIN EFFECT OF VOLTAGE, TIME AND KOH ON GAS PRODUCTION

VOLTAGE	GAS PRODUCED (cm^3)	TIME	GAS PRODUCED (cm^3)	KOH	GAS PRODUCED (cm^3)
13V	113.5	10S	31.4	0.01	32.8
12V	91.7	20S	49.3	0.015	60.7
11V	59.3	30S	66.0	0.02	60.7
10V	34.8	40S	82.5	0.025	88.8

9V	26.8	50S	97.1	0.03	83.3
FPr.	0.000				
%CV	4.56				

NaOH

INTERACTION EFFECT OF VOLTAGE, TIME AND NaOH ON GAS PRODUCTION

		NaOH				
VOLTAGE	TIME	0.01M	0.015M	0.02M	0.025M	0.03M
				GAS PRODUCED (%)		
13V	10S	29.3	30.7	39.3	42.7	56.7
	20S	42.7	53.7	73.3	87.3	90.0
	30S	56.0	72.4	102.7	126.0	136.7
	40S	70.0	95.3	135.3	165.3	181.3
	50S	82.0	113.3	165.3	210.0	225.3
12V	10S	28.0	29.3	36.0	35.3	38.0
	20S	37.3	47.3	62.7	70.0	74.0
	30S	45.3	65.3	85.3	100.0	110.0
	40S	54.7	82.7	108.0	133.3	146.0
	50S	62.0	99.3	132.0	166.7	185.3
11V	10S	25.3	24.7	29.3	31.3	28.0
	20S	34.0	38.0	47.3	53.3	49.3
	30S	40.0	48.0	58.7	70.7	67.3
	40S	46.0	58.7	71.3	90.0	87.3
	50S	52.0	70.0	85.3	107.3	105.3
	10S	19.3	20.0	25.3	20.0	19.3

	20S	24.0	24.3	32.0	26.3	26.0
10V	30S	26.7	28.0	38.7	32.7	32.7
	40S	29.3	31.7	45.3	40.0	38.0
	50S	32.0	37.3	51.3	46.0	44.0
	10S	20.0	20.0	18.7	14.7	18.0
	20S	22.0	23.3	20.7	17.3	20.0
9V	30S	23.0	25.0	21.7	18.7	22.0
	40S	24.0	27.7	22.7	19.7	24.0
	50S	25.0	29.3	23.7	21.3	26.0
FPr. (V×T×N)		0.000				
%CV		6.01				

INTERACTION EFFECT OF VOLTAGE AND TIME ON GAS PRODUCTION

	TIME				
VOLTAGE	10S	20S	30S	40S	50S
	GAS PRODUCED (%)				
13V	39.7	69.4	98.8	129.5	159.2
12V	33.3	58.3	81.2	104.9	129.1
11V	27.7	44.4	56.9	70.7	84.0
10V	20.8	26.5	31.7	36.9	42.1
9V	18.3	20.7	22.1	23.6	25.1
FPr. (V×T)	0.000				
%CV	6.01				

INTERACTION EFFECT OF VOLTAGE AND NaOH ON GAS PRODUCTION

	NaOH				
VOLTAGE	0.01M	0.015M	0.02M	0.025M	0.03M
	GAS PRODUCED (%)				
13V	56.0	73.1	103.2	126.3	138.0
12V	45.5	64.8	84.8	101.1	110.7
11V	39.5	47.9	58.4	70.5	67.5
10V	26.3	28.3	38.5	33.0	32.0
9V	22.8	25.1	21.5	18.3	22.0
FPr. (V×N)	0.000				
%CV	6.01				

INTERACTION EFFECT OF TIME AND NaOH ON GAS PRODUCTION

	NaOH				
TIME	0.01M	0.015M	0.02M	0.025M	0.03M
	GAS PRODUCED (%)				
10S	24.4	25.0	29.7	28.8	32.0
20S	32.0	37.3	47.2	50.9	51.9
30S	38.2	47.8	61.4	69.6	73.7
40S	44.8	59.2	76.5	89.7	95.3
50S	50.6	69.9	91.5	110.3	117.2
FPr. (T×N)	0.000				
%CV	6.01				

MAIN EFFECT OF VOLTAGE, TIME AND NaOH ON GAS PRODUCTION

VOLTAGE	GAS PRODUCED (%)	TIME	GAS PRODUCED (%)	KOH	GAS PRODUCED (%)
13V	99.3	10S	28.0	0.01	38.0
12V	81.4	20S	43.9	0.015	47.8
11V	56.7	30S	58.1	0.02	61.3
10V	31.6	40S	73.1	0.025	69.8
9V	21.9	50S	87.9	0.03	74.0
FPr.	0.000				
%CV	6.01				

$NaHCO_3$

INTERACTION EFFECT OF VOLTAGE, TIME AND $NaHCO_3$ ON GAS PRODUCTION

			NaHCO3			
VOLTAGE	TIME	0.01M	0.015M	0.02M	0.025M	0.03M
			GAS PRODUCED (%)			
	10S	14.7	20.0	16.7	20.7	20.0
	20S	18.7	26.7	22.0	26.0	27.3
13V	30S	20.3	32.0	26.7	35.3	34.0
	40S	22.0	36.0	32.7	40.7	39.3
	50S	24.0	40.0	37.3	47.3	45.3
	10S	14.7	19.7	17.3	18.0	19.3
	20S	18.0	23.3	20.7	23.3	25.3
12V	30S	20.0	27.3	22.7	27.3	28.7
	40S	21.7	28.3	27.7	32.7	31.3
	50S	23.3	30.3	31.3	37.3	35.3
	10S	15.7	14.3	15.7	17.3	18.6
	20S	17.7	17.3	17.7	18.3	20.3
11V	30S	20.0	18.7	19.0	19.3	22.0
	40S	21.7	20.3	20.7	21.7	23.7
	50S	23.0	21.3	22.0	23.7	28.0
	10S	0.0	17.7	16.7	21.3	20.0
	20S	0.0	19.7	20.3	23.3	21.3

10V	30S	0.0	20.7	21.3	25.0	24.0
	40S	0.0	20.7	22.3	25.3	24.3
	50S	0.0	22.0	23.3	26.0	26.0
	10S	0.0	0.0	21.0	20.0	12.7
	20S	0.0	0.0	22.3	20.0	14.7
9V	30S	0.0	0.0	23.3	21.0	16.0
	40S	0.0	0.0	24.0	22.0	16.3
	50S	0.0	0.0	24.7	22.0	18.0
FPr. (V×T×N)		0.000				
%CV		5.55				

INTERACTION EFFECT OF VOLTAGE AND TIME ON GAS PRODUCTION

		TIME			
VOLTAGE	10S	20S	30S	40S	50S
			GAS PRODUCED (%)		
13V	18.40	24.1	29.7	34.1	38.8
12V	17.80	22.1	25.2	28.3	31.5
11V	16.3	18.3	19.8	21.6	23.6
10V	15.1	16.9	18.2	18.5	19.5
9V	10.7	11.4	12.1	12.5	12.9
FPr. (V×T)	0.000				
%CV	5.55				

INTERACTION EFFECT OF VOLTAGE AND NaHCO$_3$ ON GAS PRODUCTION

			NaHCO$_3$		
VOLTAGE	0.01M	0.015M	0.02M	0.025M	0.03M
			GAS PRODUCED (%)		
13V	19.9	30.9	27.1	34.0	33.2
12V	19.6	25.8	23.9	27.7	28.0
11V	19.5	18.4	19.0	20.1	22.5
10V	0.0	20.1	20.8	24.2	23.1
9V	0.0	0.0	23.1	21.0	15.5
FPr. (V×N)	0.000				
%CV	5.55				

INTERACTION EFFECT OF TIME AND $NaHCO_3$ ON GAS PRODUCTION

	NaHCO3				
TIME	0.01M	0.015M	0.02M	0.025M	0.03M
	GAS PRODUCED (%)				
10S	9.0	14.3	17.4	19.5	18.1
20S	10.9	17.4	20.6	22.2	21.8
30S	12.1	19.7	22.6	25.6	24.9
40S	13.1	21.1	25.4	28.5	27.0
50S	14.1	22.7	27.7	31.3	30.5
FPr. (T×N)	0.000				
%CV	5.55				

MAIN EFFECT OF VOLTAGE, TIME AND $NaHCO_3$ ON GAS PRODUCTION

VOLTAGE	GAS PRODUCED (%)	TIME	GAS PRODUCED (%)	NaHCO3	GAS PRODUCED (%)
13V	29.0	10S	15.7	0.01	11.8
12V	25.0	20S	18.6	0.015	19.1
11V	19.9	30S	21.0	0.02	22.8
10V	17.7	40S	23.0	0.025	25.4
9V	11.9	50S	25.3	0.03	24.5
FPr.	0.000				
%CV	5.55				

MAIN EFFECT OF OXYHYDROGEN GAS ON EXHAUST EMISSIONS

PARAMETER	**TIME (min.)**	**OPERATION WITH DIESEL ONLY**	**OPERATION WITH HHO GAS AND DIESEL**
SULPHUR DIOXIDE(mg/m^3)	1	6210	128
	2	6370	100
	3	5085	77
	4	5131	160
	5	4500	163
	6	1867	123
	7	1867	111
	8	1867	0
	9	5970	0
	10	1867	0
	Average	**4073.40**	**86.20**

	TIME (min.)	OPERATION WITH DIESEL ONLY	OPERATION WITH HHO GAS AND DIESEL
CARBON MONOXIDE(mg/m^3)	1	186	139
	2	5970	869
	3	15500	5720
	4	206	139
	5	39000	30040
	6	21470	9590
	7	72700	1600
	8	2686	139
	9	190	139
	10	2686	1804
	Average	**16059.4**	**5017.9**
	TIME (min.)	**OPERATION WITH DIESEL ONLY**	**OPERATION WITH HHO GAS AND DIESEL**
TOTAL HYDOCARBONS(ppm)	1	7614	4095
	2	5651	3288
	3	3732	2635
	4	753	760
	5	2331	2246
	6	3555	1955
	7	1006	980
	8	2005	1554
	9	2102	1309
	10	2007	1097
	Average	**3075.60**	**1991.90**
	TIME (min.)	**OPERATION WITH DIESEL ONLY**	**OPERATION WITH HHO GAS AND DIESEL**
Oxides of Nitrogen(No$_x$ mg/m^3)	1	47	43
	2	68	64
	3	64	62
	4	76	64
	5	80	43
	6	84	68
	7	80	70
	8	31	29
	9	33	27

	10	35	30
	Average	**59.8**	**50**
	TIME (min.)	**OPERATION WITH DIESEL ONLY**	**OPERATION WITH HHO GAS AND DIESEL**
OXYGEN GAS(O_2)%	1	15.71	16.99
	2	15.22	16.86
	3	15.19	17
	4	14.78	17.38
	5	14.82	16.72
	6	15.71	16.98
	7	17	18.84
	8	18.94	19.06
	9	18.93	19.02
	10	13.3	17.5
	Average	**15.96**	**17.635**


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