ISSN 2347 - 3983
Volume 8. No. 10, October 2020
International Journal of Emerging Trends in Engineering Research
Available Online at http://www.warse.org/IJETER/static/pdf/file/ijeter878102020.pdf
https://doi.org/10.30534/ijeter/2020/878102020

Generation of Electricity Using Hydrogen Fuel Cells

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ABSTRACT

The climatic changes that are becoming visible today are the major challenges for the Global Research Community. Electricity generation is the process of generating electric power from the sources of primary energy, which is found in nature. The main aim of this work is to use hydrogen as an alternative source of energy. Hydrogen is the most abundant element in the Universe and thus, it is a never-ending source of energy. It is an energy carrier, which stores and delivers energy in the usable form, which can be produced from various domestic resources such as fossil fuels like natural gas and coal, biomass and water electrolysis. Also, Hydrogen fuel cell technology represents the alternative solutions for future clean energy systems. In the proposed work, hydrogen is converted into electric energy by using fuel cells, which do not produce any toxic gases. Fuel cells directly convert the chemical energy in hydrogen into electricity with pure water and potentially useful heat, as the only by-products. The proposed work also includes the current technologies used for hydrogen production from steam reforming, partial oxidation, auto-thermal processing and photoelectrolysis process.

Key words: Hydrogen fuel cells, Electrolysis, Fuel cell technology, Electricity generation.

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1. INTRODUCTION

Hydrogen is the most abundant element on earth, which consists of only one proton and one electron. A fuel cell combines hydrogen and oxygen to produce electricity, heat and water. Fuel cells are similar to batteries, where both perform the energy conversion by a chemical reaction into the usable electric power. Fuel cells can produce electricity as long as hydrogen is supplied and these operate best when we supply pure Hydrogen[1]. Some fuels like natural gas, methanol, gasoline can also be reformed to produce the hydrogen required for fuel cells. Fuel cells can be used to produce power for an electric motor as well as directly producing electricity in place of a generator. In both the cases, they facilitate the replacement of a gasoline or diesel engine. Also, fuel cells do not produce any greenhouse gases or air pollutants. The product of the chemical reaction is only water and a small amount of heat. Fuel cells are mainly used as power sources in remote locations like spacecraft, remote weather stations, large parks, communication centres, rural locations such as research stations, military applications etc. The fuel cell system running on hydrogen is very compact and light weight. The annual production of hydrogen is estimated to be around 55million tons with its consumption increasing by approximately 6% every year. At the end of October 2019, there were around 80 fuel cell power plants operating in the United States with a total of 190MegaWatts of electric generation capacity. Both the electrolytic and plasma processes are highly efficient for hydrogen production, but these are considered as energy intensive processes.

2. OBJECTIVES

- To increase the electrical efficiency and durability of various fuel cells used for power production.
- To reduce the cost to a level competitive with conventional technologies.
- To increase the energy efficiency of production of hydrogen from electrolysis of water and renewable sources while reducing the capital costs.
- To reduce the rare earth elements, thereby reducing the greenhouse effect in the atmosphere.
- To reduce the dependence on imported hydrocarbons
- To contribute to economic growth and provide employment in country.

3. VARIOUS METHODS TO PRODUCE HYDROGEN GAS

Hydrogen can be produced by various processing technologies such as thermal processing, electrolytic processing, photolytic processing and so on.

I. ELECTROLYSIS PROCESS

Electrolysis is the process for the production of hydrogen which can be extensively used in near future. As of now, approximately, 4% of the hydrogen gas is produced by this process. Electrolysis of water, which is the method of breaking into hydrogen and oxygen, is commercially under existence since the year 1890. It can be defined as the process in which a direct current passes through the two electrodes in water solution, resulting in breakage of chemical bonds present in water molecules into hydrogen and oxygen atoms. Chemical Reactions [2].

$$2H_2O(l) \longrightarrow 2H_2(g) + O_2(g)$$

The number of hydrogen molecules produced is twice the number of oxygen molecules. Generally, the electrolysis process is done at room temperature only. The most commonly used electrolyte in water electrolysis is sulphuric acid. The electrodes are chosen as Platinum(Pt), as it does not react with sulphuric acid. Also, in this method, we do not have production of any greenhouse gases. And the oxygen produced can be furthermore utilised in the industrial applications. Because of all these factors, electrolysis have become a highly demanding technology now a days.

II. PHOTOELECTROLYSIS PROCESS

Photoelectrolysis is the renewable source of hydrogen production, which is least expensive and most effective method among renewable sources. The photoelectrode is a semiconducting device, which absorbs solar energy and simultaneously creates the required voltage for the direct decomposition of water molecules into Oxygen and Hydrogen. It utilizes a photoelectrochemical(PEC) light collection system for driving the electrolysis of water. When the semiconductor photoelectrode is submerged in an aqueous electrolyte exposed to solar radiation, it generates electrical energy [4].

The photoelectrode is comprised of photovoltaic, catalytic and protective layers, which can be modelled as individual components. The photovoltaic layer is produced from light absorbing semiconductor materials. The semiconductors with wide bands provide the necessary potential for splitting of water.

III. STEAM REFORMING PROCESS

Steam reforming is the least expensive process for production of hydrogen which requires modest temperatures. The main advantage of this method is its high efficiency and low operation and production cost. The materials used for this method are natural gas and hydrocarbons, methanol and some other oxygenated hydrocarbons.

Chemical reactions

$$C_mH_n + mH_2O\ (g) \rightarrow mCO + (m + 0.5\,n)\,H_2$$
$$C_mH_n + 2mH2O\ (g) \rightarrow mCO_2 + (2m + 0.5\,n)\,H_2$$
$$CO + H_2O\ (g) \longleftrightarrow CO_2 + H_2$$
$$CH_3OH + H_2O\ (g) \longleftrightarrow CO_2 + 3H$$

Firstly, the hydrocarbon material is mixed with steam and fed into a tubular catalytic reactor. During this time, H_2/CO gas mixture is produced with lower content in CO_2. Inorder to achieve the required reaction temperature, oxygen is added for combusting part of the raw material inside the reactor. Later, the cooled product gas is fed into the CO catalytyic converter. This converter converts the carbon monoxide into carbon dioxide and hydrogen by means of steam[6]. To avoid the deactivation of catalyst, the raw material used should be free of sulphur compounds. Here, less expensive nickel catalysts are only preferred. In this method, higher is the H : C atom ratio, lower the carbon dioxide emission. The main drawback of this system is that it has high production of carbon dioxide.

IV. PARTIAL OXIDATION (POX)

Partial oxidation method is mainly proposed for commercial applications like automobiles. The raw materials preferred here are methane and biogas. This method is the non-catalytic process, in which the raw material is gasified in the presence of oxygen and steam[3]. The temperature and pressure range generally used for this method are 1300-1500^{0}c and 3-8Mpa range.

Chemical reactions

$$CH_4 + O_2 \rightarrow CO + 2H_2$$
$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$
$$CH_4 + H_2O\ (g) \rightarrow CO + 3H_2$$

The mixture formed by using the partial oxidation method mainly contains, CO, CO_2, H_2O, H_2, CH_4(Methane), H_2 (Hydrogen Sulphide) and COS(Carbon Oxysulphide). Some part of the gas is burnt to provide sufficient amount of heat for the endothermic processes. Since the method does not require the use of catalyst, there is no necessity of removing sulphurous elements from natural gas. Some catalysts can be added to this system in order to reduce the operating temperature. Then this method can be referred to as Catalytic Partial Oxidation Method.

V. Autothermal Reforming

This method is the combination of both steam reforming and partial oxidation processes. The process does not require any external heat and hence it is very less expensive compared to other two methods. Also, the process can be shut down and can be started very rapidly, simultaneously producing a larger amount of hydrogen than the POX process[5]. The method is very much preferable to "Gas to Liquid" fuel industry because of its low capital cost and relative compactness.

4. Feasible Process to Produce Hydrogen – ELECTROLYSIS METHOD

Although we have many methods of generating hydrogen, electrolysis is the most efficient method which does not produce any greenhouse gases or any other pollutants in the environment. And also, electrolysis method is capable of producing high purity hydrogen. Water electrolysis has an electrical efficiency of 70-80%, so that producing 1kg of hydrogen, which has a specific energy of 143MJ/kg or about 40kWh/kg, requires 50-55 kWh of electricity.

Electrolysis is the most efficient method for production of hydrogen. It is the process of using electricity to split water molecules into both hydrogen and oxygen. The entire reaction takes place in the unit called Electrolyzer. These electrolyzers range in size from small scale distributed hydrogen production to large scale production.

Chemical Reaction

$$2H_2O(l) \longrightarrow 2H_2(g) + O_2(g)$$

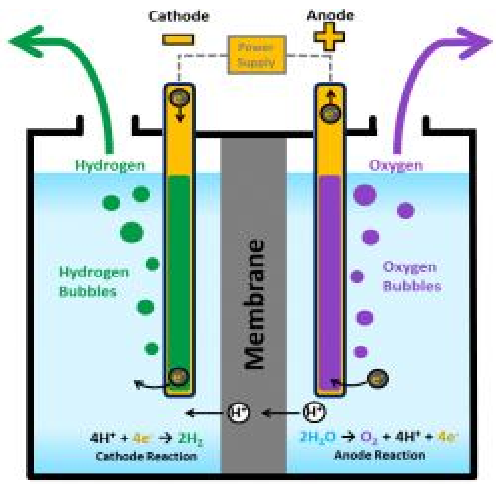

Figure.1: Electrolysis Method

4.1 WORKING PRINCIPLE

Electrolyzers consist of an anode and cathode separated by an electrolyte. The functioning of electrolyzers differs slightly due to the type of electrolyte material used. A 100% efficient electrolyzer requires approximately 39kWh of electricity to produce 1kg of Hydrogen. The following are the types of electrolyzers:

- **Polymer Electrolyte Membrane Electrolyzers (PEM)**

In PEM, the electrolyte used is a solid plastic material. Here water reacts at the anode to form oxygen and positively charged hydrogen ions (protons). The electrons flow through the external circuit and the hydrogen ions will move selectively across the PEM to the cathode. At the cathode, hydrogen ions combine with electrons from the external circuit to form hydrogen gas.

Chemical Reactions

Reaction at anode:

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

Reaction at cathode:

$$4H^+ + 4e^- \rightarrow 2H_2$$

- **Alkaline Electrolyzers**

Alkaline electrolyzers operate mainly with the transport of hydroxide ions (OH^-) through the electrolyte from cathode to the anode. Hydrogen is generated on the cathode side. These electrolyzers use a liquid alkaline solution of sodium or potassium hydroxide. Solid alkaline exchange membranes can also be preferably used.

- **Solid Oxide Electrolyzers**

These electrolyzers use solid ceramic materials as the electrolyte, which selectively conducts the negatively charged oxygen ions (O^{-2}) at the suitable temperatures and generate hydrogen. At cathode, water combines with electrons from the external circuit to form hydrogen and negatively charged oxygen ions. The oxygen ions pass through the solid ceramic membrane and react at the anode to produce oxygen gas, while generating the electrons for the external circuit. These electrolyzers must operate at high temperatures around 700-800^{o}C, which is sufficiently enough for the solid oxide membranes to function properly. These can effectively use the heat available at the highest temperatures to decrease the amount of electrical energy required to produce hydrogen from water[7].

The most commonly used technology in electrolysis is alkaline based but Proton Exchange Membrane (PEM) and Solid Oxide Electrolysis Cells (SOEC) have also been developed with the challenge of corrosion seals, thermal cycling and also chrome migration. The PEM electrolyzers are more efficient compared to alkaline based systems as they do not have any corrosion problems or seal issues as in SOEC. Here, we prefer to alkaline based systems as these are having very low capital cost.

Fuel cells directly convert the chemical energy in hydrogen into electricity. Hydrogen powered fuel cells are pollution-free and also have two or three times the efficiency of traditional combustion technologies[8]. Any conventional combustion based power plant can generate electricity at an efficiency of approximately 33percent. But fuel cell systems can generate electricity at an efficiency of approximately 60percent. Also fuel cells can power up any portable application which uses batteries ranging from hand-held devices to portable generators. These can also be used to power transportation for personal vehicles, trucks, buses, marine vessels etc.

5. GENERATE ELECTRICITY USING FUEL CELLS

A single fuel cell consists of an electrolyte sandwiched between two electrodes, anode and cathode. The bipolar plates on either side of the fuel cell helps in distributing gases and hence serve as current collectors. Fuel cells take in hydrogen and oxygen from the air and produces electricity, heat and water. As the fuel cells do not produce any greenhouse gases, it can be considered as the ideal solution to provide electrical power.

Hydrogen + Oxygen = Electricity + Water Vapour

The following figure shows how fuel cell produces power.

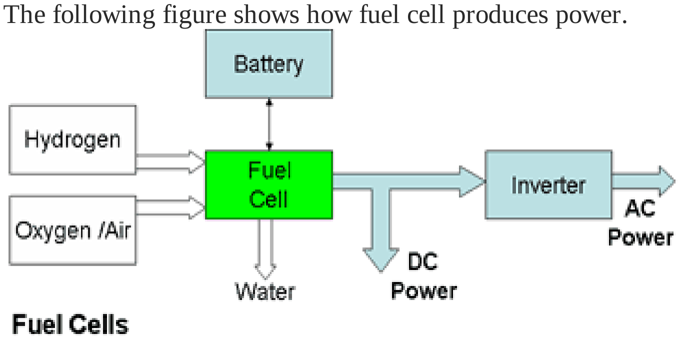

Figure. 2: Process carried out in Fuel Cells

Unlike batteries fuel cells do not store energy. These provide electrical energy only when the active chemicals are supplied to the electrodes [9].

5.1 TYPES OF FUEL CELLS

The following are the types of fuel cells that are used for generating electric power:

- **Proton Exchange Membrane (PEM) Fuel Cell**

This fuel cell is also called the Polymer Electrolyte Membrane Fuel cell. Generally, fuel cells use hydrogen as the fuel and oxygen from the air as the oxidant. The chemical reaction using PEM fuel cell is given by:

$$2H_2 + O_2 \Rightarrow 2H_2O$$

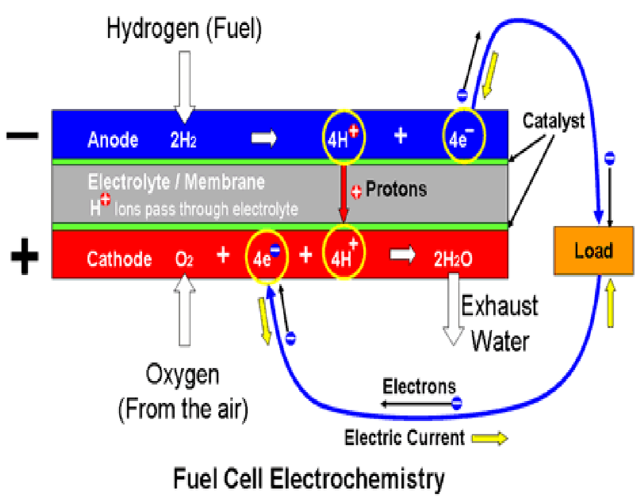

Figure.3: Proton Exchange Membrane (PEM) Fuel cell

The electrodes used here are made of porous carbon, which allows the active gases to pass through. The surface of the electrode supports platinum catalysts [12]. Electrolyte is a thin, fragile sheet of acidic, solid organic polymer about 50microns thick. This thin sheet allows the passage of Hydrogen ions and is impermeable to electrons. All the acidic compounds are fluids containing free hydrogen ions, which act as the charge carriers in the fuel cells.

Hydrogen is given to the anode, where it gets oxidised losing electrodes during the entire process. The positive hydrogen ions (or protons) migrate across the electrolyte through the membrane to the anode. And at the same time, the electrons travel round the external circuit to the cathode. The oxygen is supplied to the cathode where it is reduced, while picking up the electrons and the ions from the hydrogen to form water. The electron flow between the anode and the cathode occurred due to the chemical reactions in the cell represent the conventional electric current flowing in the opposite direction [10]. The electric current produced can be used in the external circuit.

Generally, catalysts are used to increase the rate of oxidation at the anode and the rate of reduction at cathode.

These allow the chemical reaction to take place at a lower temperature. The catalyst used here is of platinum, which is very expensive and also sensitive to poisoning by very small amounts of Carbon Monoxide.

- **Direct Methanol Fuel Cells (DMFC)**

The working of DMFC is similar to the PEM fuel cell. The electrolyte used here is a polymer and the charge carriers are the hydrogen ions. The Liquid Methanol (CH_3OH) is fed to the anode, where it is oxidised in the presence of water generating carbon dioxide (CO_2). At cathode, oxygen combines with the hydrogen ions and electrons from the external circuit to produce water[11].

The chemical reactions are given by:

At anode:

$$CH_3OH + H_2O \Rightarrow CO_2 + 6H^+ + 6e^-$$

At cathode:

$$3/2\ O_2 + 6H^+ + 6e^- \Rightarrow 3H_2O$$

The overall reaction in the fuel cell is represented as:

$$2CH_3OH + 3O_2 \Rightarrow O_2 + 4H_2O$$

These fuel cells work at low operating temperatures in the range of 50°C to 120°C. DMFCs have low efficiency and power density compared to PEM fuel cells and hence, PEM fuel cells are preferred mostly[13]. The ability to use liquid fuel coupled with the elimination of the reformer make these fuel cells to be used in most of the applications.

6. Estimation of Generation of Electricity in kWh

The power produced from the fuel cells depends on various factors such as including the fuel cell type, size, operating temperature and the pressure at which gases are supplied. A single fuel cell can produce approximately one volt or even less, which can be useful for even small applications. Inorder to increase the amount of electricity generated, individual fuel cells can be combined in series to form a stack. Here, we refer the term "fuel cell" as the entire stack as well as the individual cell. Depending upon the type of application, a very few or as many as hundreds of individual cells may be layered together. And hence, fuel cells have a wide range of applications from laptop computers (50-100Watts) to homes(1-5kW), vehicles(50-125kW) and central power generation (1-200MWatts or more).

Any fuel cell which is 60% efficient requires 1.66kWh of chemical energy to generate 1kWh of electrical energy. As 1kWh = 3.6 megaJoules, one kg of hydrogen contains 141.8 mega Joules. That is

(1.666 x 3.6)/141.8 = 42.3 grams of hydrogen.

7. DATA COLLECTION

The amount of hydrogen extracted from a gallon of water can be known easily by using the molecular weight of water (H_2O), Hydrogen and Oxygen. This is represented below[15]:
The molecular weight of water is the sum of two hydrogen molecules and one oxygen molecule. That is,
The molecular weight of two hydrogen molecules
(2H) = 2 x 1=2
The molecular weight of one oxygen molecule
(1O) = 1 x 16
Hence, the total molecular weight = 2 + 16 = 18
For each molecule of water, we get two molecules of hydrogen in the Electrolysis process. We know that the density of water is $1g/cm^3$. Therefore, in a gallon of water (around 3.785litres or $3785cm^3$), the mass of water will be equal to 3785gms. That is, one mole of 6.02×10^{23} molecules of water is equal to the molecular weight of water (18grams per mole)[19]. Hence, 3785grams represent 1.265×10^{26} molecules of water. Now, if every single one of the water molecules is converted into hydrogen, we would get hydrogen as twice as that of water quantity or 2.53×10^{26} molecules of hydrogen. As hydrogen is a diatomic molecule (H_2), we get 1.265×10^{26} molecules of hydrogen. At 1Atmospheric pressure and 273K, 1mole of hydrogen fills approximately 22.4L of volume. Therefore, 1.265×10^{26} molecules or about 210moles, would be able to fill 4707Litres of volume.

8. CONCLUSION:

Currently, there is a tremendous amount of research work done towards the development of hydrogen gas generation technologies. At present, the most developed technology to generate electricity is fuel cell technology. Also to decrease the dependency on fossil fuels, various significant developments in the hydrogen generation technologies have been in use, which use renewable sources like biomass and water. Also, it should be noted that hydrogen can be produced from a variety of feedstock, which is almost available everywhere.

Development of new technologies may decrease the world's dependence on fuels, which are obtained primarily from the unstable regions. The ability of hydrogen gas to be produced from a wide variety of feedstock and also, using all these wide variety of processes in each and every region of the world would be able to produce much of its own energy. Hence, it is clear that hydrogen which is obtained from various sources serve as an ideal fuel form available in the market.

Hydrogen can play an important role in future by replacing the imported petroleum, we currently use in our personal vehicles like cars, trucks etc.

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