A Review on Basic Fuel Cell Design and Applications

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Abstract

The call to researching alternate power sources has been heard in many industries and markets and has lead to several new and renewed research fields in recent years. One such alternate power source is fuel cells. A growing type of cell in the automotive industry and other applications is the proton exchange membrane, PEM, hydrogen fuel cell.

Hydrogen fuel cells are based on simple chemistry, using pure hydrogen and oxygen to make H₂O. The byproduct is then processed using extra power to create hydrogen and oxygen. This process can be perpetuated using only solar power, a fuel cell, and the extra processor, an electrolyzer. The process of creating and destroying water to make electricity can lead to zero emission cars, a revolution in how batteries are defined and used, and reduced home energy costs.

This paper will go into more detail about the processes and systems of a PEM fuel cell. After the basics have been laid out applications already in use will be described and several theories for further applications of the cells will be illustrated.

1. Introduction

A device that converts energy from a chemical reaction to produce electricity is called a fuel cell. Fuel cells come in several varieties, producing different byproducts, using different reactants, and running at different operating temperatures. The PEM fuel cell uses only hydrogen and oxygen or hydrogen and air. By an electrochemical reaction the PEM fuel cell exhaust is only water. Applications of the PEM fuel cell appear to be environmentally friendly, drawing them into the buzz word market of ‘green’ technology.

The fuel cell, excluding the subsystems around it, has no moving parts. A closed cell system uses hydrogen and oxygen to create electricity, water, and heat. Subsystems of the fuel cell and fuel cell stack are required for water, heat, fuel, reactants, power, and entire system management. Cells that do not regulate temperature, pressure, flow rates, humidity and power will fail or have significantly reduced performance and efficiency.

The first fuel cell was developed in 1839 by William Grove. The cell would have been large in comparison to more modern models, but it still would have produced electricity. All cells today are researched and produced to also make electricity as an alternate to burning fossil fuels. Fuel cells have no environmentally harmful byproducts making them a clean alternate fuel source. The automotive industry has been adopting fuel cells into their designs for many years.

PEM Hydrogen fuel cells are broken into 2 types of systems, a closed system or an open system. In a closed system the reactants and are never released from the system. Water created by the fuel cell system can be used to make the reactants, starting a cycle. The optimum hydrogen economy cycle would follow Figure 1. The device in the system to break down the water from the cycle is called an electrolyzer. An electrolyzer uses an
external source, solar for example, to break down water into hydrogen and oxygen. The fuel cell system has many subsystems to move the reactants through a series of processes. Hydrogen is first delivered to the system from a pressurized tank and moves to the cell membrane. At the membrane the hydrogen electron passes through a current as the proton passes through the membrane.

![Figure 1 Optimum Hydrogen Economy](image)

The hydrogen proton and electron pair up with oxygen on the other side of the membrane to form water. An open system generally uses hydrogen and air as the system reactants but all processes inside the cell follow a similar pattern.

2. Fuel Cell Subsystem Processes
The fuel cell requires precise conditions for humidity in the cell membrane, for the operating temperature, for the reactant and byproduct flow rates, and for its power output. A subsystem is required for heat, water, power, and reactant flow rates.

Heat and water management are one subsystem in the closed fuel cell system. Water from the cathode side of the cell membrane is deposited to a holding tank. The tank should be designed to hold as much water as the system can produce, following mass conservation for a mass flow rate. The mass flow rate of the cell is simplified by assuming a control volume with one inlet and one outlet. Water from the tank is used in the radiator and humidifier. The radiator removes the heat from the cell system to regulate the cell operating temperature.

The power required to move a vehicle varies based on drag, friction coefficients, mass of the object, and gear efficiency. A fuel cell’s most basic purpose is to create electricity to do some kind of work based on device requirements, such as for a vehicle. This process
takes place in the Membrane Electrode Assembly, MEA, which sits between the bi-polar plates. The bi-polar plates are used to connect one cell to another to create the stack. Electricity produced requires a power management system, regulating voltage using thyristors and GTO thyristors to match power requirements of a device. A capacitor, on-board battery, or external power sources are examples of additional power management tools to help a fuel cell cover any immediate changes in power consumption.

A device powered by a fuel cell may have changing power needs that do not happen immediately. These needs can be met by altering the efficiency and performance of a fuel cell. Efficiency and performance will change when the amount of hydrogen being released to the MEA is adjusted to match changing power requirements. Adjusting the hydrogen requires changing the oxygen flow rate by the same ratio so that cell performance and efficiency does not lower to unexpected values.

Hydrogen and oxygen are stored in pressurized tanks as a gas, liquid, or solid. Hydrogen enters on the anode side of a cell through a flow field. Anode flow fields are designed to optimize hydrogen distribution through channels to the cell membrane. Channels in the flow field must be carefully designed or efficiency and performance problems will result from starving the cell of its fuel source. After the hydrogen atom is delivered and broken down it passes as a proton through the fully saturated Proton Exchange Membrane, PEM.

Oxygen flow is determined by flow fields on the cathode side of the cell. If oxygen flow rates do not keep the ratio of oxygen to hydrogen correct cell efficiency will drop. Real fuel cell efficiency is determined by multiplying thermal efficiency, voltage efficiency, and fuel efficiency. Fuel efficiency is the ratio of fuel used to generate a current to the total fuel used.

A fuel cell has a membrane that is surrounded by 2 electrodes. Each electrode has a platinum catalyst where the reaction between the electrolyte and electrodes causes an electron to leave the hydrogen atom. The electron travels through a current to the other side of the membrane. The proton left over from the reaction must meet the electrons in a separate space to form water.
The electrons are channeled through the next platinum electrode where the hydrogen protons are deposited after passing through the membrane. A membrane is designed to separate the reactions taking place so that the work being done from the reaction is captured and organized to make meaningful work. Additionally, the membrane must allow a proton to pass through it.

A fuel cell produces electricity, heat and water. Electrons from the breakdown of hydrogen are channeled through an external current to be used for meaningful work. After hydrogen protons have passed through the membrane they bond with electrons and oxygen flowing at constant rate through the cathode side of the cell. The cathode side of the cell is where water and heat are produced.

Each must be removed from the system so that cell efficiency and performance do not drop. If water is not removed quickly enough it will flood the cell membrane and if too much is removed too quickly the membrane will dry out, each changing the performance and efficiency of the cell.

Heat must be removed using a heat and water management subsystem. Increasing or decreasing temperature will adjust performance and efficiency. Increasing temperature value will increase cell performance but decrease efficiency based only on thermodynamically reversible voltages.\(^9\)

Alone, a fuel cell will produce no more than 1.23 V. Because of that, a single fuel cell is useless for almost all applications unless many cells are connected in series, called a fuel cell stack, to make a higher voltage value. Fuel cell stacks require even distribution of reactants not only across the cell membrane but to each individual cell. A stack is designed to power devices that require more power than what a single cell can provide. Most single cells cannot provide enough power to do any meaningful work for any electronic device, except for a LED. Stacks have all the same reactants and byproducts of any cell but the way each is delivered or removed from the system varies. To
determine the amount of power a stack would use a ratio of surface area of all membranes in the stack to the number of stacks is used.

3. Research and Applications

Fuel cells have been used in transportation, stationary power, and micro applications. Some of these applications have been in use for many years. For example, NASA was using a fuel cell in the 60’s for their Gemini and Apollo programs and many automobile companies today have a version of a fuel cell vehicle\(^2\).

Stationary power applications are not limited to creating power for just a building. These can be applied to any system that requires power, such as hotels or homes. The over 2500 stationary fuel cell systems in the world achieve a 40% efficiency rating\(^4\). Future fuel cells will be able to power laptops and cell phones based off of current research.

It’s expected that college students will use a computer before they graduate. In fact, it’s common place that every college student owns a laptop. Like many electronics, a laptop requires batteries and all batteries run out of power. Eventually batteries lose the ability to hold a charge. Fuel cells would be a reasonable replacement for batteries because they can be recharged by replacing the fuel source. The technology to replace batteries could revolutionize a lot of markets. Everything that has ever used a battery could be powered by fuel cells.

One of the many applications for fuel cells is robotics. The military has contracted out to a company called Kuchera Defense Systems. During testing the military found batteries in the system to last for only an hour and approached the company with the problem. Kuchera used another company, Jadoo, to produce a fuel cell to run the robot. To increase the run time of the robot Jadoo applied solid storage of hydrogen using a material called metal hydrides. The company dubbed their new device, the N-Stor. N-Stor communicates valuable information about the fuel cell and hydrogen through a digital readout. The result was more than doubling the runtime of the robots from the 100 watts of power produced\(^1\).

General Motors and Honda, two major automobile companies, have made working models of fuel cell cars that are being tested by civilians. There is 4.2 kg of compressed hydrogen is used in General Motors, GM, vehicle and it travels about 165 miles\(^6\). Honda’s vehicle can travel 240 miles on 3.92 kg of compressed hydrogen, a more efficient vehicle than GM’s\(^7\). By applying a system such an N-Stor GM or Honda could increase the runtime of their vehicles to better compete with gas and other electric models.

As more mobile hydrogen fuel cell systems are designed and produced the more people will come to rely on them as people have done with batteries and fossil fuels. Many applications of mobile fuel cell production have already been developed, such as portable power systems.
Portable cells should be applied to smaller electronic devices. For example, a modern college student has a number of devices they use throughout their day. Before exam week, a student will set their alarm on their cell phones, text some number of friends, and fall asleep while studying and listening to their mp3 player. When they wake, the student will grab their bag, books, laptop, and mp3 player. By mid-day of a busy exam week their laptop is dead, cell phone on its last leg and mp3 player drained. If a backpack carried a small fuel cell then all of this could be avoided and additional benefits would still exist. On the coldest of days and hottest of days a cell system could run a body control system to help cool someone down or keep someone warm. This can be accomplished with batteries but recharging batteries only works for so long before a charge can’t be held. Design would be restricted because of a batteries size, shape, and weight. A fuel cell that utilizes a unique membrane design, such as a cylindrical design could be made to fit the mold of the backpack. A stack design of 5 cells, similar to Figure 3, would be about the size of a D-cell battery, running around 2.4 volts for a power output of 1.02 watts.

![Figure 3 Cylindrical Cell Model (Rakesh)](image)

The options for stack design have changed to fit into the already designed bag. A backpack could be lined with tube membranes that are linked together to create membrane chains.

Utilizing fuel cell technology has opportunities in stationary power systems. Stationary systems include anything from cell towers to homes and hospitals.
Home owners pay many utility bills, including electric, heating, and water bills. This is a lot of energy that is put into a system that constantly losses energy. The energy for the system comes from the main power supply in the America, coal, which produces a lot of harmful byproducts for people to breathe in. Perhaps, the current power grid in America could be re-evaluated to be more environmentally conscious.

The average Americans home uses 11040kWh annually\(^5\). This means the average American home will use 1.26 kW of power. A PEM fuel cell stack can produce up to and beyond 5kW of power\(^8\), passing the needs of an average residence. An environmentally clean system or ‘green technology’ could therefore be theoretically be integrated into a home. It would need a large tank for holding water, a solar cell, an electrolyzer, a fuel cell stack, a nutrient device, and a water purification device.

As water is drawn from a large holding tank it is purified to be pure water with no extra chemicals or nutrients. Electricity produced from a ‘green’ source, for example a solar cell, and pure water is used in an electrolyzer. The resulting hydrogen and oxygen would be stored in tanks for later use in a fuel cell. Essentially, the stored hydrogen and oxygen act as batteries for the house because they are drawing in power as it’s available from a solar cell and storing it for when it’s needed. The pure water produced from the cell can be fed into a nutrient device so that it becomes potable. If water is pure it’s damaging because more energy is used to drink and process the water than what is taken from it. Once the water is potable it can be introduced into the already existing water system of the home. All waste water is brought back into the system and purified to be used in the electrolyzer.
Fuel cells produce a lot of heat. The cell system described above would use a PEM fuel cell that runs close to 100°C. By altering the radiator for a fuel cell the excess heat can be used to heat the home.

Conclusion

Fuel cells are ready for further development and research to be integrated into an already existing system. Designs have been proven in systems such as automobiles and robotics and are being explored in micro fuel cell applications such as laptops. The fuel cell is proving to be a versatile device and is preparing to take over standard power grids and portable power applications. Undergraduate studies in continuing research and developing fuel cell designs could help set CMU as a leading university in alternate energy design and application.

References