VEHICLES WITH HYDROGEN-AIR FUEL CELLS

Frano Barbir

Proton Energy Systems, Wallingford, CT, USA

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Summary

Fuel cell vehicles are still in the development and demonstration phase. All major car manufacturers have demonstrated prototype fuel cell vehicles and announced plans for production and commercialization. The most promising fuel cell technology appears to be the polymer exchange membrane (PEM) fuel cell. Fuel cells directly convert the chemical energy of fuel into electricity through an electrochemical reaction. Fuel cell vehicles are therefore electric vehicles. Their efficiency is higher than the efficiency of vehicles with internal combustion engines, particularly in a driving cycle.

The result of the fuel cell electrochemical reaction is pure water, and this zero emission feature is one of the most important advantages of fuel cell vehicles. Because of the lack of hydrogen infrastructure, car manufacturers are working on onboard fuel reformers as a way to bring fuel cell vehicles to the market sooner. However, they recognize hydrogen as the ultimate transportation fuel.

This paper is a review of automotive fuel cell technology, including the PEM fuel cell construction and principle of operation, operational conditions, and fuel cell system design and configuration options. Technology status and near-term technical targets are presented. An overview of fuel cell vehicles demonstrated to date is also included.

1. Introduction

Fuel cells, particularly proton exchange membrane (PEM) fuel cells, have the potential to replace the internal combustion engine in automobiles. The race to develop a viable

fuel cell vehicle and to bring it to the market began during the 1990s continues in the first decade of the twenty-first century. Almost all major car manufacturers are currently working on development of fuel cell vehicles. Several prototypes have been demonstrated, and plans for production and commercialization have been announced.

The major drivers for the development of fuel cell technology are efficiency and low emissions. The efficiency of fuel cells versus the internal combustion engine is often misrepresented. These two technologies are intrinsically different and have different efficiency-power characteristics. While an internal combustion engine has the maximum efficiency at or near its maximum power, the fuel cell system has its maximum efficiency at partial load. Because of that, the efficiency of a hydrogen-fueled fuel cell propulsion system in a typical driving schedule, where an automobile engine operates most of the time at partial load, is approximately twice that of an internal combustion engine. If another fuel is used (such as methanol or gasoline) and reformed onboard, the efficiency of a fuel cell propulsion system is lower than the efficiency of a hydrogen fuel cell system, although still higher than the efficiency of the internal combustion engine.

A hydrogen fuel cell does not generate any pollution. The only by-product is pure water, which leaves the system as both liquid and vapor. The amount of water produced by a fuel cell propulsion system in a typical driving schedule is comparable to the amount of water produced by an internal combustion engine. If another fuel is used (such as methanol or gasoline) and reformed onboard, the propulsion system has some emissions generated in the reforming process, but those emissions are in general still much lower than the emissions from an internal combustion engine and would typically qualify it for ultra-low emission vehicle (ULEV) status.

The cost of the fuel cells is often considered to be an obstacle for commercialization. However, several studies conducted by or on behalf of major car manufacturers have shown that fuel cells could be produced cost competitively, assuming mass production manufacturing techniques.

The biggest obstacle to the introduction of fuel cell vehicles is the lack of hydrogen infrastructure. Hydrogen is not available at gas stations, and establishing necessary hydrogen infrastructure would require significant capital cost. Because of this, car manufacturers are attempting to develop an onboard reforming system so that fuel cell vehicles could be brought into the market sooner using the existing fuel infrastructure. However, this brings additional complexity to the system, results in lower efficiency, and generates some emissions.

2. Proton Exchange Membrane Fuel Cell

The most promising fuel cell technology for automotive propulsion is the proton exchange membrane (PEM) fuel cell because of its simplicity, efficiency, quick start-up, modularity, and low power density.

The crucial component of a PEM fuel cell is obviously the membrane that is impermeable to the reactant gases and conducts protons. Almost all of the PEM fuel

cells developed up to 2000 used the same perfluorosulfonic acid polymer (best known under the trade name Nafion[TM]). Some other polymers (such as PBI or PEEK) have been suggested and tried, but Nafion-based membranes dominate the market.

On each side of the membrane there is an electrode with a catalyst layer firmly attached to the membrane. The electrode on the fuel side is called the anode, and the electrode on the oxidant side is the cathode. The catalyst layer can be deposited directly on the membrane and then a porous, electrically conductive substrate (such as carbon fiber paper or carbon cloth) attached to it, or the catalyst layer can be deposited on the substrate and then attached/pressed onto the membrane. A typical catalyst for PEM fuel cells is platinum dispersed on high-surface area carbon particles. At present, platinum (Pt) loading is about 0.3 mg/cm², but electrodes with Pt loading as low as 0.001 mg/cm² have been demonstrated. In case the fuel fed into the fuel cell is not pure hydrogen, and especially if it contains carbon monoxide, an alloy of Pt-Ru (ruthenium) is used as a catalyst on the fuel side.
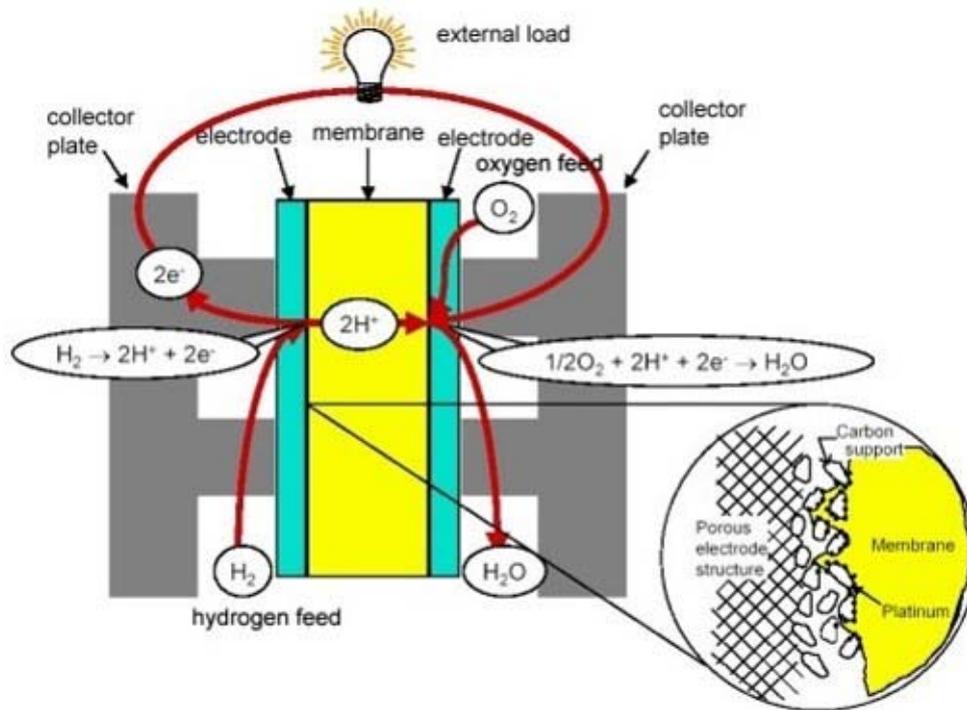

Figure 1. Schematic representation of a PEM fuel cell

Fuel (hydrogen or hydrogen-rich gas) and oxidant (oxygen or oxygen-containing gas such as air) are fed on the opposite sides of the membrane, as shown in Figure 1. The reactant gases are distributed over the entire electrode/membrane area through channels housed by the current collector plates, which are firmly pressed into the electrode substrate.

These plates are made of electrically conductive material, typically graphite or a graphite/polymer mixture. Metallic plates are also being developed, but the corrosive fuel cell environment limits the choice of materials and typically requires special coating.

Hydrogen at the anode catalyst surface splits into protons and electrons. The protons go through the proton-conductive membrane. Nafion-type membranes conduct protons only when they are well hydrated. The electrons go through the electrically conductive porous electrode (anode), through the current collector plate, through the electrical circuit where they perform work, and come back through the current collector plate on the other side of the membrane, then through the porous cathode structure to the catalyst sites where they meet with oxygen molecules from air and the protons that traveled through the membrane and combine in an electrochemical reaction resulting in pure water. The produced water is removed from the cell with the flow of depleted air. Depending on the operating temperature and pressure and inlet air humidity, product water can leave the fuel cell as a vapor or liquid.

In the case of a single cell, the current is taken directly from the current collectors. In multicell configurations, the cells are stacked in series with current collectors physically separating the adjacent cells while at the same time connecting them electrically (the anode of one cell to the cathode of the adjacent cell). Current is typically taken from the bus plates or bus poles attached to the first and last current collector in the stack (Figure 2).
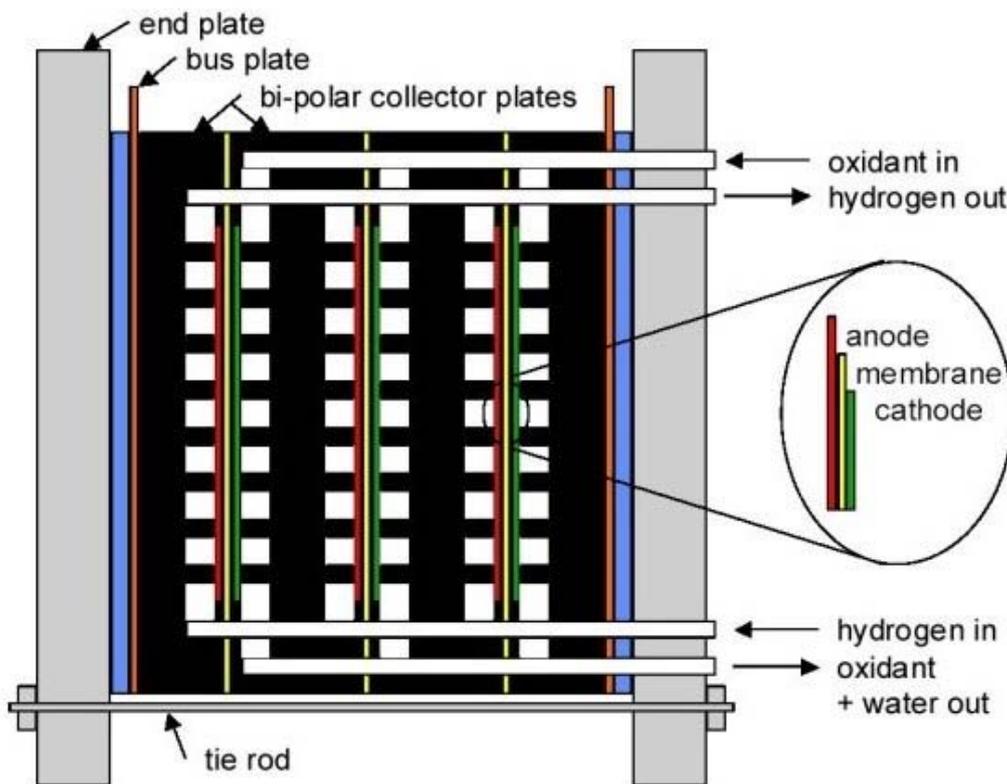

Figure 2. Schematic representation of a PEM fuel cell stack

The theoretical voltage of the fuel cell hydrogen-oxygen reaction is 1.229 V. However, because of various losses, this voltage is in practice much lower. It is typically about 1 V at open circuit, and then it drops farther down as a function of current being generated and drawn from the cell. Figure 3 shows a typical fuel cell polarization curve, i.e. cell voltage as a function of current density. In the stack of cells, the voltage of individual cells adds up to the stack voltage. Nominal operating voltage of a fuel cell is an

arbitrary design variable, typically about 0.7 V. Higher selected voltage would result in lower current density, and lower power density, and therefore such a fuel cell stack would require more cells or a larger active area than the fuel cell producing the same power but with a lower selected nominal cell voltage. The efficiency of a fuel cell is directly proportional to its voltage. Therefore, the efficiency of a fuel cell is tradable with its size.
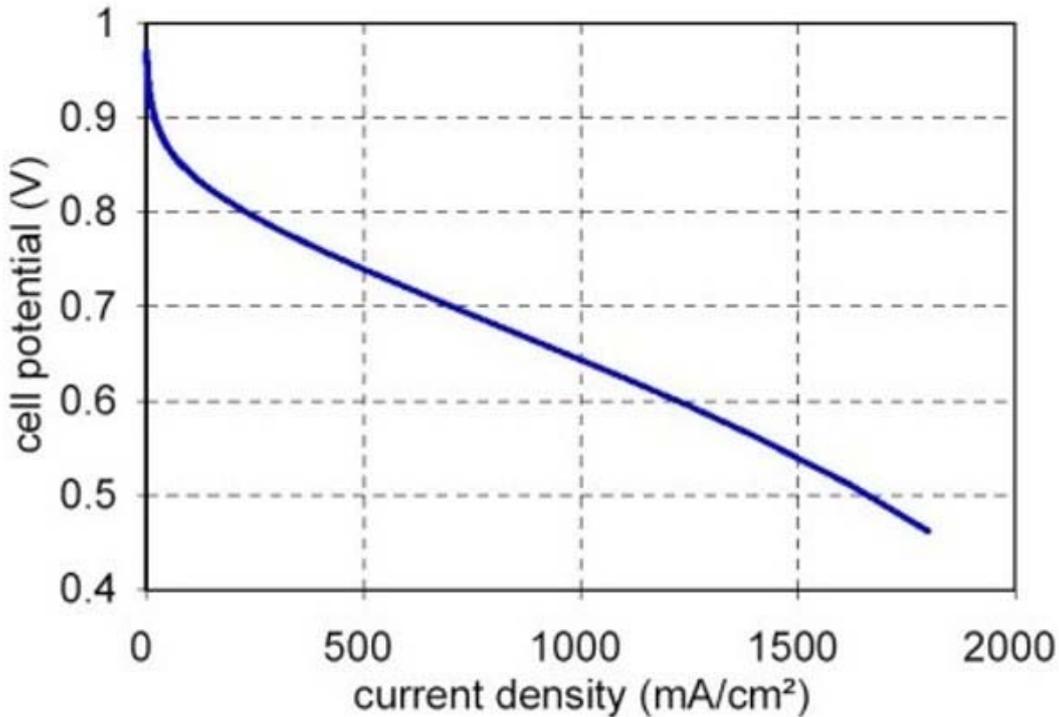

Figure 3. Typical PEM fuel cell polarization curve H_2/Air; 3 bar, 60 °C

Hydrogen consumption in a fuel cell is directly proportional to electrical current generated, according to Faraday's Law:

$$\dot{m}_{H2} = \frac{M_{H2} \cdot I \cdot N_{cell}}{nF} \qquad (1)$$

where $\dot{m}_{H2}$ = mass of hydrogen consumed (g/s)
  M_{H2} = molecular mass of hydrogen (2.016 g/mol)
  I = electrical current (amperes)
  N_{cell} = number of cells
  n = number of electrons involved in reaction (2 per mol of H_2)
  F = Faraday constant (96485 C)
Because power (in watts) produced by a fuel cell is:

$$P = V_{cell} \cdot I \cdot N_{cell} \qquad (2)$$

where V_{cell} = individual cell voltage (Volts), instead of $I N_{cell}$ in equation (1), it might be more convenient to use P/V_{cell}.

Oxygen consumption is similarly:

$$\dot{m}_{O2} = \frac{M_{O2} \cdot I \cdot N_{cell}}{nF} \tag{3}$$

where M_{O2} = molecular mass of oxygen (31.9988 g/mol)

n   = number of electrons involved in reaction (4 per mol of O_2)

For automotive fuel cell applications, oxygen comes from air. The air requirement (in g/s) is:

$$\dot{m}_{air} = \frac{\dot{m}_{O2} \lambda_{O2}}{g_{O2}} \tag{4}$$

where λ_{O2} = oxygen stoichometric ratio, i.e. the ratio of actual oxygen supply and oxygen

consumed in the reaction

g_{O2} = mass fraction of oxygen in air (0.232)

To minimize the parasitic power needed for pumping air through the fuel cell, λ should be as close to 1 as practically possible. However, a larger number results in better fuel cell performance, because it results in higher oxygen concentration through the fuel cell. Typically, the oxygen stoichiometric ratio is 2:2.5.

The PEM fuel cell is operational at room temperature, but the typical operating temperature is 60 °C to 80 °C. Operating pressure has a significant effect on fuel cell performance. In general, higher pressure results in a higher polarization curve.

Ionic conductivity of Nafion-type membranes is a strong function of water content. Each proton is accompanied by several water molecules. Because of this electro-osmotic drag, the anode side would dry out.

However, due to a concentration gradient, some water travels through the membrane in the opposite direction, i.e. from cathode to anode. Net water transport is a function of membrane thickness, current density, cell design, and humidity of reactant gases.

To prevent drying of either the anode or the cathode side, the reactant gases are typically humidified before entering the cell.

3. Fuel Cell System

A functional fuel cell requires an operating system with the following functions: fuel supply, air supply, water management, heat management, power conditioning, and controls. Figure 4 shows a schematic diagram of a typical fuel cell system.
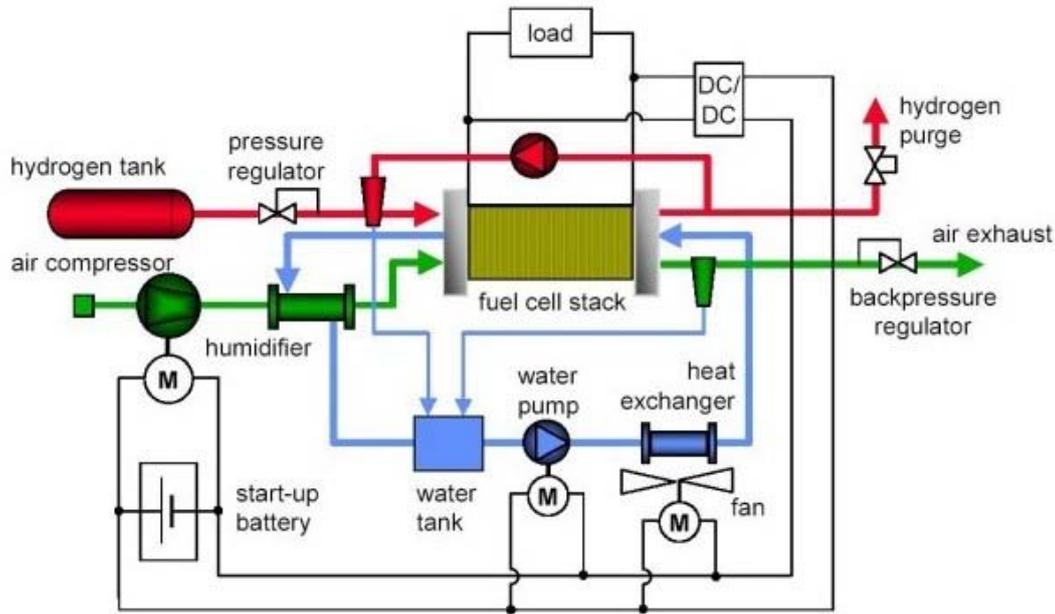
Figure 4. Schematic of an automotive fuel cell system

When the fuel cell uses pure hydrogen as a fuel, the fuel supply system is relatively simple. Pressure in hydrogen storage is always higher than the fuel cell operating pressure, regardless of the type of storage (pressurized gas, liquid, or metal hydride). To reduce the hydrogen pressure to the fuel cell operating pressure, a pressure regulator is needed on the pipeline connecting the fuel storage and the fuel cell. There is no need to regulate the hydrogen flow—hydrogen is simply consumed by the fuel cell at a rate that is proportional to current generated and replenished from the storage due to the pressure difference. To maintain the membrane hydration, hydrogen must be humidified before entering the fuel cell. Some fuel cell designs do not require external humidification—hydrogen is humidified internally inside the fuel cell stack using either the water from the cathode side or an external source of water. To remove the water from the anode compartment, hydrogen must be either recirculated while the water is separated and removed or intermittently purged. Recirculation can be accomplished by a pump or ejector.

Air supply is more complicated. A blower or a compressor is needed to supply the required amount of air at the desired pressure. Automotive fuel cell systems operate at pressures between atmospheric and 3 atm to 4 atm. In a pressurized system, the pressure is maintained by the backpressure regulator at the air outlet. Air must also be humidified to prevent drying of the inlet portion of the membrane. This water together with product water generated on the cathode side must be expelled from the fuel cell stack with the excess flow of air. A water separator at the fuel cell outlet removes water from the depleted air. In most of the temperature/pressure combinations, the amount of liquid water collected at the cathode outlet is sufficient for humidification of both reactant gases.

Although a higher operating pressure results in better fuel cell performance, the choice of operating pressure is not that straightforward. A fuel cell performance gain at elevated pressure might be offset by the parasitic power needed to run an air

compressor. Because of these parasitic losses, the systems operating at low pressure are usually more efficient than the pressurized systems. However, a low-pressure system needs more water for humidification. To be able to preserve neutral water balance, the system has to be operated at a lower temperature or additional water recovery equipment must be a part of the system. Either way, a low-pressure system needs larger water and heat management equipment.

The desired fuel cell operational temperature (typically between 60 °C and 80 °C) is maintained by flowing a coolant through the fuel cell stack. Some systems use deionized water for cooling, but to prevent freezing, antifreeze coolant is preferred to water. The heat is then ejected from the coolant to the environment through a radiator-type heat exchanger. The fuel cell radiator is usually much larger than an internal combustion engine's radiator because of the fuel cell's lower operating temperature.

Water is collected from the anode and cathode exhausts and then used to (re)humidify the inlets. Several humidification schemes have been proposed and used in fuel cell automobiles, such as:

- Membrane humidifiers in which reactant gas flows across a wetted membrane. The membrane is kept wetted by the flow of hot water. This humidifier can be external or internal, i.e. an integral part of the stack.
- Membrane humidifiers in which the membrane is kept wetted by the exhaust gas saturated with water vapor.
- In-stack humidification using porous bipolar plates. For obvious reasons, this method is feasible only for the systems operating at low pressure.
- Spray humidifiers where the exact amount of water is injected into the reactant gas. The heat for evaporation of this water must also be supplied (for example, using fuel cell coolant).
- Steam injectors, where the exact amount of steam is injected in the reactant gas. The steam is also a heat carrier, and no additional heat is required; however, heat must be used to generate the steam.

A fuel cell system does not require any sophisticated control schemes. The only parameters that must be actively controlled are air supply, humidification, and operating temperature. Air supply is controlled by a variable-speed compressor with mechanically (potentiostat) or electronically (PID loop) controlled motor speed. Humidification is controlled either passively by the flow of reactant gas or actively with a computer-controlled metering pump or solenoid valve. The temperature of the system is regulated in the same fashion as in an internal combustion engine vehicle, i.e. by on-off or multistage radiator fan or fans.

The fuel cell generates direct current at voltages that vary with the load. Depending on the size of the fuel cells and the type of the propulsion electric motor, power conditioning might be necessary. This can include one or more of the following configurations:

- DC/AC conversion—converting DC into AC
- DC/DC conversion—boosting up the fuel cell voltage to the voltage of the DC buss
- DC/DC conversion—scaling down the fuel cell voltage to 24 V or 42 V to run the auxiliary components

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Biographical Sketch

Dr. Frano Barbir is the Director of Fuel Cell Technology and Chief Scientist with Proton Energy Systems, Wallingford, CT. Since 1992, Dr. Barbir has been directly involved in research and development of PEM fuel cells and fuel cell systems. He led an engineering team that built and successfully demonstrated five fuel cell vehicles. Concurrently with working in industry, he held positions at the University of Miami as an Adjunct Professor in the Mechanical Engineering Department and as a Project Director with the University's Clean Energy Research Institute. He is teaching a fuel cell engineering course at the University of Connecticut. He has more than 130 publications on hydrogen and fuel cells in scientific and technical journals, books, encyclopedias, and conference proceedings. He is an active member of the International Association for Hydrogen Energy (Internet Editor and Associate Editor of the *International Journal of Hydrogen Energy*), the Electrochemical Society, and the American Solar Energy Society. He has a Ph.D. degree in Mechanical Engineering from the University of Miami, and an M.Sc. in Chemical/Environmental Engineering and Dipl.Ing. degree in Mechanical Engineering, both from the University of Zagreb, Croatia.