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DOI: 10.7251/JTTTP2401051I
UDC: 629.11+621.352]:539.211

REVIEW

Fuel Cell Technologies in Automotive Applications

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Received: March 27, 2024
Accepted: April 1, 2024

Abstract: This paper provides an analysis of the latest fuel cell technology through a general description and characteristics of the six most important fuel cell technologies, indicating their use and future development in the automotive industry.

Keywords: Fuel Cell, Electric Vehicle

INTRODUCTION

Fuel cells are seen by many people as a key solutions for the 21st century, enabling clean efficient production of power and heat from a range of primary energy sources.

A fuel cell produces energy from an electrochemical reaction, very similar to a battery. Batteries store energy and when they are used up, the battery must be discarded or recharged using an external power supply, by starting an electrochemical reaction in the reverse direction.

Fuel cell uses an external energy supply and may operate indefinitely as long as it is equipped with a source of hydrogen and an oxygen (usually air) source. Hydrogen atoms react with oxygen atoms electrochemically during oxidation to create water; electrons are released within the process and flow as an electrical current through an external circuit [1].

The chemical energy in hydrogen is directly converted into electricity by fuel cells, the only by-products being pure water and potentially useful heat. Fuel cell systems can produce up to 60 percent efficiency of electricity and even higher with cogeneration [2].

A new phase in the development of motor vehicles has gone through several technological phases and today we are definitely in a new era that is primarily related to steering autonomy and vehicle propulsion systems [3].

PRINCIPAL FEATURES OF FUEL CELLS

A fuel cell is an electrochemical device which converts the chemical energy of a fuel and an oxidant directly into electrical energy. The basic physical structure of a single fuel cell consists of an anode, a cathode and an electrolyte sandwiched between the two electrodes. Bipolar plates are placed on either side of the cell and enable distribute gases and current to the external circuit.

In a fuel cell, hydrogen gas flows to the anode through channels, as depicted in Figure 1, where a catalyst allows the hydrogen molecules to separate into protons and electrons. The membrane is permeable for protons to pass through it. The protons are conducted to the other side of the cellthrough the membrane and the negatively charged stream of electrons is conducted through an external circuit to the cathode. This flow of electrons is electricity, which can be used to power an electric motor [2].

The electrochemical reactions in case of a fuel cell with an acid electrolyte are:

Anode reaction:

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

Cathode reaction:

$½O_2 + 2H+ + 2e- \rightarrow H_2O$

Overall reaction:

$H_2 + ½\, O_2 \rightarrow H_2O + heat$

Air flows to the cathode through channels on the other side of the cell. At the cathode, the electrons returning after doing work react with oxygen in the air and the protons, which have moved through the membrane inside the cell to form water. This union is an exothermic reaction, where heat iis generated that can be used outside the fuel cell.

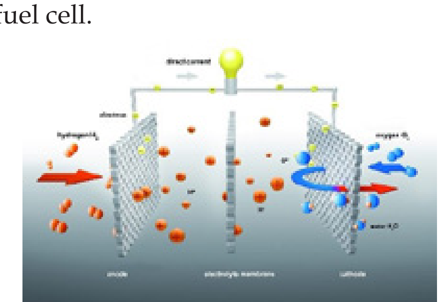

Figure 1. Fuel Cell Principle

The Advantages of Fuel Cells

Compared with traditional fossil fuel-powered electrical generators, the use of fuel cells has many advantages:

- Higher Efficiency: The higher volumetric and gravimetric efficiency of fuel cells is a result of the chemical production of electric energy directly from the fuel used, without combustion. On the other hand, in a Carnot thermic cycle the electric generation efficiency is restricted by its lower combustion efficiency.
- *Low Chemical, Acoustic, and Thermal Emissions:* Due to lower fuel oxidation temperatures, we have the case that fuel cells produce less greenhouse gases, carbon dioxide and nitrogen oxides for kilowatt of power generated. Also, in absence of any moving parts in fuel cells, noise and vibration are negligible.
- *Modularity and Flexibility:* A single fuel cell produces less than one volt of electrical potential. Fuel cells are stacked on top of each other and connected in series to produce higher voltages. Desired power output and individual cell performance dictates the number of cells in a stack, which ranges from a few hundreds of W to several hundred of kW up to some MW.
- *Low Maintenance:* It is relatively easy to identify and substitute a damaged or malfunctioning cell contained inside a stack due to high modularity of Fuel cell systems, which leads to lower maintenance costs.
- *Fuel Flexibility:* For fuel cells requiring low temperatures, hydrogen is most widely used as pure gas for operation. The fuel flexibility depends on the operative temperature range of the type of fuel cells used. In principle, higher the temperature, less pure the gas that the fuel cell can use to generate hydrogen.
- *No pollutants:* Fuel Cells produce only pure water & heat as by-product. No Carbon dioxide/ monoxide gases are produced.

The disadvantages are as follows

- Fuel cells costs are still too high and unsuitable for the substituting the technologies based on fossil fuels. To compete with current internal combustion engine technology for automotive applications a cost of €10 to €50 per kW and an operation life of 4000 hours is required.
- Hydrogen is one of the main fuels for fuel cell technologies. However, it is expensive and is lacking in a wide network for its production and distribution.
- The life cycle and the degradation time of fuel cells technologies is still insufficiently known, especially for high-temperature technologies that have proven to be the best for electric power generation.
- Hydrogen is a flammable and potentially explosive gas and is difficult to compress a suitable quantity of hydrogen in small fuel containers. This is precisely the reason why the use of low-temperature fuel cells in the automotive market is very limited [4].

TYPES OF FUEL CELLS AND APPLICATIONS

Actually there are many technologies of fuel cells available on the market, and each one of those is characterized by: the operative temperature range, the type of fuels which can be used, the type of catalyst used by the cell and the efficiency ratio of the energy conversion.

Today we can talk about several types of fuel cells technologies that exist on the market and where they are used. Therefore, we can define the following division of fuel cells into:

- Alkaline - AFC
- Polymer Electrolyte Membrane - PEMFC
- Direct Methanol - DMFC
- Phosphoric Acid - PAFC
- Molten Carbonate - MCFC
- Solid Oxide - SOFC

FUEL CELLS FOR AUTOMOTIVE APPLICATIONS

Fuel Cells based vehicle propulsion has zero emissions, much higher performance than ICE or battery vehicles and a higher degree of well-to-wheel efficiency than ICE or BEVs. The Fuel Cells EVs have a higher range and shorter refueling time compared to battery-EVs [7–13].

A series of PEMFC powered cars have been designed by Daimler-Benz since 1994 in collaboration with Ballard. In 1997 Daimler-Benz launched a 640 km range methanol-fueled car for the first of these vehicles.

Japanese automakers launched their Fuel Cells EVs. One Fuel Cells EV manufacturer has a 100 kW PEFC stack with a power density of 3 kW/liter, powered by two 700 bar H_2 tanks providing a range of 650 km. The hybrid system is equipped with a 1.6 kWh Ni-MH battery that is also used for regenerative braking.

The PEM fuel cell was an obvious choice in the late 90s due to its rapid start-up time. However, one of the main problems associated with hydrogens is its on-board storage in passenger vehicles. Hydrogen can be contained in metal hydrides or as compressed gases as cryogenic fluid. The compressed gas hydrogen tanks are bulky, even though hydrogen is compressed to 450 bar. It takes around 40–50 liters of volume for storing 1 kg of pure hydrogen. The fuel quantity that is stored onboard is dependent upon the fuel efficiency and the range needed.

Diesel engines for road vehicles achieve an efficiency of 48 percent (best engines, one stage with the most powerful loads). SOFC is the natural alternative in many heavy vehicle applications because of its ability to run on biogas, bio-ethanol, bio-methanol and syngas reformed hydrogen (Figure 2) [4].

There are no CO_2 emissions from a fuel cell operating on hydrogen except for water. The overall system's GHG emissions depend however on the hydrogen production's GHG emissions intensity. In the applications of Fuel Cells, strong environmental benefits are therefore expected.

Fuel Cells reduce noise emissions in vehicle applications, especially at low speed. Other benefits include the reduction of gear changes, improved possible reliability, compatibility with other electrical and electronic devices, and different safety design choices for cars.

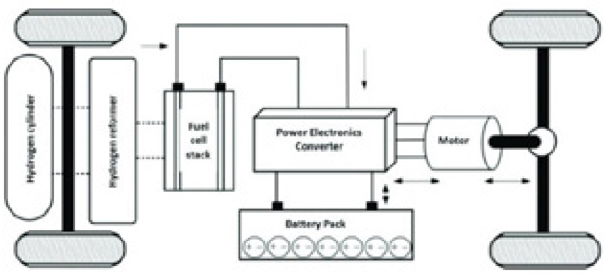

Figure 2. Fuel Cell System for Electric Vehicle (FCEV)

CONCLUSION

Fuel Cells provide the electric energy without polluting environment, due to which they are looked as potential source of energy for automobiles. As can be read from the above, many fuel cell technologies exist and each of these technologies has its own strengths and weaknesses. Each technology is well-suited for specific application environments and has many issues that actually prevent their full commercialization. There are certain Fuel Cells which require pure Hydrogen for reaction inside the Fuel Cell and other types require hydrocarbons/certain compounds which disintegrates into Hydrogen inside an Fuel Cells. On one hand, storage of compressed Hydrogen is a practical difficulty, while operating an Fuel Cells at low temperature poses another challenge in an automobile. Another challenge posed is excessive cost of technology for developing and manufacturing the Fuel Cells.

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Table 1. Fuel Cell Comparison [2, 5, 6]

	AFC	PEMFC	DMFC	PAFC	MCFC	SOFC
Operating temperature	<100°C	60-120°C	60-120°C	160-220°C	600-800°C	800-1000°C
Electrolyte	KOH	Perfluoro sulfonic acid	Perfluoro sulfonic acid	H_3PO_4 immobilized in SiC matrix	Li_2CO_3 –K_2CO_3 eutectic mixture immobilized in Υ-LiAlO2	YSZ (Yttria stabilized zirconia)
Anode reaction	$H_2+2OH- \rightarrow 2H_2O+2e-$	$H_2 \rightarrow 2H^+ +2e-$	$CH3OH+H2O \rightarrow CO2+6\ H^+ + 6\ e-$	$H_2 \rightarrow 2H++2e-$	$H2+CO3^{2-} \rightarrow H2O+CO2+2e-$	$H_2+O_2- \rightarrow H_2O +2e-$
Cathode reaction	$1/2O2+H2O+2e- \rightarrow 2OH-$	$1/2O_2+2H^+ +2e- \rightarrow H_2O$	$3/2\ O_2+6\ H^+ +6e- \rightarrow 3\ H_2O$	$1/2\ O_2+2H^+ +2e- \rightarrow H_2O$	$1/2O_2+CO_2+2e- \rightarrow CO_2^{2-}$	$1/2O2+2e- \rightarrow O_2-$
Electrode materials	Anode: Ni Cathode: Ag	Anode: Pt, PtRu Cathode: Pt	Anode: Pt, PtRu Cathode: Pt	Anode: Pt, PtRu Cathode: Pt	Anode: Ni-5Cr Cathode: NiO(Li)	Anode: Ni-YSZ Cathode: LSM
Application		Transportation space, military energy storage systems		Combined heat and power for decentralized stat. power systems	Combined heat and power for stationary decentralized systems and for transportation (trains, boats,...)	
Realized power	Small plants 5-150 kW modular	Small plants 5-250 kW modular	Small plants <5 kW	Small medium sized plants 50 kW-11 MW	Small power plants 100kW-2 MW	Small power plants 100-250 kW
Electrical efficiency (LHV)	60%	60% direct H_2 40% reformed fuel	35%	40%	50%	60%
Life time	Not available	2,000-3,000 h	1,00 h	> 50,000 h	7,000-8,000 h	1,000 h