Fuel cells as a future of automotive industry: A review of current developments

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Abstract. Fuel cells are more and more applied in the automotive industry in recent decades. This applies to both special equipment, such as forklifts, and personal automobiles. They are already serious competitors for BEVs (battery electric vehicles) and will likely compete with ICE (internal combustion engine) vehicles in the future. This study provides an overview of the latest developments in the use of fuel cells in transport.

1. Introduction
The main reason of hydrogen integration to the energy sector consists in the environmental protection. With the hydrogen energy use only water vapor is released into the atmosphere. Hydrogen has been especially actively promoted recently as a fuel for automobiles. The state of the atmosphere in large cities is a matter of serious concern due to the overcrowding of automobiles running on traditional motor fuels. This concerns both the emission of carbon dioxide and, first of all, the products of incomplete combustion: carbon monoxide and fragments of hydrocarbon fuels harmful to health.

This study provides an overview of the latest developments related to the applications of fuel cells in the transport sector. In particular, economic and environmental comparative studies with other types of vehicles, modeling of fuel cells (FC) and vehicles, the influence of design features and degradation on FC performance are analyzed.

2. Operational concept of fuel cells
Unlike thermal power plants, in which chemical energy of the fuel is first converted into heat and then into work (electricity), in a fuel cell, chemical energy is directly converted into electrical energy. An open-loop process (close to isothermal), not a cycle, is implemented. Therefore the restrictions associated with the cycle efficiency are eliminated. Theoretically, all the chemical energy of the fuel can be converted into electrical energy in FC. However, the practical implementation faces serious challenges.

The main challenge in the FC design is to carry out the reaction of the fuel with the oxidizer in an electrochemical way close to reversible. For this, in the general case, both components of the reaction should be firstly converted into ions. The ionization of the fuel and the oxidizer is carried out at moderate temperatures due to the use of active catalysts, including platinum group metals.

The structural diagram of a hydrogen fuel cell is presented in Figure 1. The fuel cell consists of a negatively charged electrode (anode), a positively charged electrode (cathode), and an electrolyte membrane.
In the FC structure, the initial products for the electrochemical reaction are hydrogen and oxygen. In this case, hydrogen fuel is supplied through the anode of the fuel cell and oxygen is supplied through the cathode outlet. During the reaction, hydrogen decomposes into positive protons and negative ions on the anode side. Protons are transferred from the anode to the cathode through the electrolyte membrane, allowing only positively charged particles to pass through. Electrons, negative ions at the end of the anode, tend to reunite with the positively charged particles and move to the cathode side along the external circuit. Hence, this flow of electrons in the external circuit generates electricity at the load. In nature, molecules cannot remain in an ionic state, so they immediately recombine with other molecules to return to a neutral state. At the cathode, oxygen reacts with protons and electrons to form water and heat. Both the anode and cathode contain a catalyst to accelerate electrochemical processes. [6], [7]

A typical proton exchange membrane (PEM) fuel cell has the following reactions:
Anode: \( \text{H}_2 \text{(gas)} \rightarrow 2\text{H}^+ + 2\text{e}^- \).
Cathode: \( \frac{1}{2} \text{O}_2 \text{(gas)} + 2\text{H}^+ + 2\text{e}^- \rightarrow \text{H}_2\text{O} \text{(liquid)} \).
The full reaction: \( \text{H}_2 \text{(gas)} + \frac{1}{2} \text{O}_2 \text{(gas)} \rightarrow \text{H}_2\text{O} \text{(liquid)} + \text{electrical energy} + \text{waste heat} \).

Reagents are transferred by diffusion and / or convection to catalyzed electrode surfaces where electrochemical reactions take place. The water and waste heat generated by the fuel cell must be constantly removed because they can lead to the malfunction of proton exchange membrane fuel cells (PEMFC).

The performance characteristics of a typical fuel cell are important for evaluating the size of the power circuit to be used in various applications. In this regard, it is important to know the current-voltage characteristic of the fuel cell. The dependencies of voltage on current density for a single element of a typical design operating at 40 °C and under standard atmospheric pressure are shown in Figure 2. [7]

The key points are as follows:
• Even the open-circuit voltage is less than the theoretical value of 1.2 V.
• Rapid initial voltage drop occurs, then the voltage drops more slowly and more linearly.
• Faster voltage drops can be observed at higher current densities.
Figure 2. Current-voltage characteristic of a fuel cell

Figure 3. Dependence of hydrogen consumption on the fuel cell power

Figure 3 shows the dependence of hydrogen consumption on the fuel cell power. As can be seen from the graph, the dependence is almost linear.

3. Development of fuel cells and electrical systems for automobiles

Researchers Nancy L. Garland et al. [3] consider the durability and performance of fuel cells. Comparative analysis of gasoline and electric vehicles showed that electric vehicles powered by hydrogen FC have the lowest greenhouse gas emissions, as well as the lowest oil consumption per mile. The most expensive vehicles to operate are battery electric vehicles, with a range of 400 miles with cost around 30 ¢ / mile to nearly 65 ¢ / mile. The high cost is a result of the large number of batteries required to obtain the desired range. The rest of the cars will cost around 25-30 ¢ / mile to operate. This analysis shows the existence of benefits from a set of options.

Lúcia Bollini Braga et al. [4] in their research carried out a comparative technical, economic and environmental analysis of electric vehicles with FC type PEM and diesel generator vehicles. The technical analysis showed the advantages of FC over a diesel generator based on energy aspects. The economic analysis shows that FC are currently not economically competitive compared to an ICE driving a generator with the same performance. The environmental analysis was based on the concepts of CO₂ equivalent, pollution metric and environmental performance. The FC does not emit pollutants directly, and the emissions associated with this technology are mainly associated with the production of hydrogen. The environmental efficiency of PEMFC was 96% when produced by ethanol reforming. For a diesel generator system, this parameter reaches 51%.

A study by Attuluri R. Vijay Babu et al. [5] focuses on parametric analysis of PEM-type fuel cells used in vehicles to improve performance. The experimental results demonstrate the significant influence of the temperature of elements on the performance, while other parameters cause variation only in the activation polarization region and in the concentration polarization region.

Many researchers highlight the advantages of an electric vehicle design that combines fuel cells with storage batteries. In such a set-up, the operation efficiency depends on how the power supplies are controlled and matched. Hao Li [6] proposed a methodology for determining the optimal sizing of components. It is used for proper configuration of a hybrid battery-fuel cell system in terms of degradation experienced by the battery and fuel cell stack over the life of the vehicle. The results showed that by reducing the size of the battery, the life of the fuel cell stack was reduced. This is explained by the FC need to meet the peak power demand by operating under high load for a long time. According to the study findings, a decrease in the size of the fuel cell stack leads to the fuel consumption rate increase due to the need to maintain the same power level.

Alejandro J. del Real et al. [7] in their paper present a complete dynamic model of a fuel cell. It is a control-oriented model that can be used to design the controller and optimal operational strategies for the development of fuel cell-based power systems. The model has been validated with a 1.2 kW PEMFC, which can be considered a benchmark since it is investigated in many studies as a good
example of the state of development in this technology. The model was validated on a real site, proving that the simulated data matched the experimental data.

R.E. Silva et al. [8] study the prediction of output voltage drop caused by degradation during the nominal operating state of a PEMFC stack. The prediction performance is evaluated for the output voltage of the two FC during long-term operation (1000 hours). The test results have confirmed that the proposed methodology is well adapted to predict degradation in fuel cell systems.

M. Muthukumar et al. [9] in their research paper investigated the influence of design parameters on the performance of the PEMFC. For this, full three-dimensional models were developed, according to which the necessary design parameters of the fuel cells were determined to obtain the highest current density at the output.

Researchers P.Karthikeyan et al. [10] also focused on the optimization of the operating parameters of fuel cells and achieved an increase in power by 3%.

Brahim Gasbaoui et al. [11] developed a control system for an all-wheel drive vehicle with fuel cells. Digital simulation in Matlab Simulink has demonstrated satisfactory results.

Huicui Chen et al. [12] analyze the endurance test protocols of PEMFC. Based on the analysis and demonstration of various protocols of many universities and research institutions in different countries, the main characteristics and applicable protocol environments were summarized.

The analysis showed that a comprehensive and effective endurance test protocol should consist of many typical operating conditions such as dynamic load condition, starting condition, no-load condition, power condition, and overload condition. The purposes of testing and different driving conditions can be met by adjusting the proportion of times of various typical conditions throughout the duration.

The authors conclude that future research work should focus on the following aspects, (1) the mechanism of FC degradation during each operating mode, such as initial stop, idle and cyclic loading, (2) Study on the design of the endurance assessment protocol methodology of fuel cells taking into account configurations and transmission control strategies; (3) The main factors affecting the deterioration of the life of automotive fuel cells and their eliminating methods.

G.J.Offer et al. [13] examined hydrogen-fueled electric vehicle and battery options for the future transportation system, focusing on quantitative comparisons of different platforms in terms of life cycle costs in 2030.

A number of interesting conclusions can be drawn from their analysis:

First of all, in terms of capital costs, any electric vehicle is much more expensive than conventional ICE vehicles in 2010. However, capital expenditures could be significantly reduced by 2030. Moreover hybrid electric vehicles with FC (FCHEV) show the lowest capital costs, followed by battery electric vehicles (BEV) and fuel cell electric vehicles (FCEV). However, IEC vehicles will still be cheaper than their competitors in 2030.

Secondly, in terms of fuel costs, the accurate prediction of future costs is impossible. However, some reasonable assumptions have been made. The efficiency of each transmission has a notable impact on the cost of fuel per mile. Electric vehicles achieve much higher mileage units per GJ of energy than vehicles running on hydrogen or gasoline. In 2030, BEV and FCHEV are relatively insensitive to changes in fuel (electricity) costs, while FCEV and ICE show significant sensitivity to hydrogen and gasoline costs, respectively. This is partly due to the varying efficiency of the transmission.

Thirdly, when it comes to total lifecycle costs over 100,000 miles, FCHEVs appear to be slightly cheaper than BEVs, but show a broader overall sensitivity to total (capital and operating) costs. Both classic cars and FCEV have much higher life cycle costs than FCHEV and BEV, about 1,75 times higher.

With regard to BEVs, a separate study was conducted on battery size in terms of range and vehicle efficiency. It can be seen that the life cycle cost of a BEV is very sensitive to the size of the battery and that the economy of a BEV is the cheapest if the size of the battery can be minimized, for example in city automobiles with only 50 miles of mileage.
Based on this research, some recommendations can be made:

1. Hydrogen FC electric vehicles may play a specific role in the road transport of the future, but the best platform for FC integration is the battery-powered hybrid electric vehicle. This platform also has an advantage based on a technology roadmap, which in the near future starts with hybrids with ICE and electric motors.

2. Reducing capital costs for BEVs, FCEVs and FCHEVs should be a key goal for the permanent development and minimization and recycling of platinum, lithium and other valuable raw materials used in these technologies.

3. Various technologies for increasing the range (ICE in the near future, fuel cells in the long term) can compete for a place in the electrified transport network, with economic, social and political issues affecting the choice of platforms by consumers and recharging or refueling.

Panini Kolavennu et al. [14] examined the feed system for an electric fuel cell vehicle that uses methane as a hydrogen source. According to the study, when the engine fuel demand suddenly rises, a delay in producing the required amount of hydrogen arises. To eliminate this lag, a battery and a shift controller have been added. The controller switches between the fuel cell and the backup battery. The effectiveness of this scheme is verified by simulation in Matlab on a power profile obtained from a realistic speed profile of a small car.

Pouria Ahmadi et al. [15] deals with the simulation of hydrogen fuel cell vehicles and the development of a life cycle assessment tool for calculating and comparing the environmental impact of hydrogen passenger cars with conventional vehicles, using the example of the Toyota Mirai and Toyota Camry.

Since fuel cell vehicles are often equipped with a battery to store braking energy, the driving cycle can significantly affect the performance of FC vehicles. To investigate the impact of driving patterns, several of them are considered, fuel economy and emissions are calculated and compared.

On the other hand, degradation of fuel cells is another major problem. It is mainly caused by starts / stops, acceleration / deceleration and high vehicle load.

Four different driving models were presented: UDDS - The U.S. EPA Mandatory Dynamometer Test for fuel economy, which reflects city driving conditions and is used to test light duty vehicles in Surrey City, New York City, and highways.

The results show that the driving cycle has a significant impact on both overall emissions and fuel economy. The findings also demonstrate minimal emissions compared to New York, COS and UDDS driving cycles. The reason is the fastest speed of highway profile compared to the other speed profiles. Although this profile does not have a lot of starts / stops, it makes the vehicle run in a semi-stable state that is much more stable than other speed profiles. The results also indicate that degradation of fuel cells leads to an increase in average fuel consumption of about 23%.

One of the many ways that engineers can improve fuel economy is through the use of regenerative braking systems. The best possible outcome for these systems is when the speed profile has many starts / stops at relatively high speeds.

4. Conclusion
The tendency towards alternative energy sources has intensified due to the depletion of fossil fuels and volatility in oil prices, the need to improve the efficiency of existing transport technologies and the growing trend towards the use of clean technologies to minimize the impact of global warming. The impact of the fuel used in vehicles and the corresponding values of carbon emissions on global warming is one of the most important factors shaping the future of the automotive industry. Accordingly, the increase in the share of electric vehicles depending on the conditions of each country is inevitable. Electric vehicles have numerous advantages such as low fuel and maintenance costs, low noise levels and high efficiency and zero emissions. However, since the battery is the only source of energy and limit the range of electric vehicles, they are preferred in urban environments with limited distances.
The FC are becoming widely used in the field of electric vehicles, and this progress is expected to accelerate in the coming years. This type of vehicle is expected to become more common in modern life along with the reduction in the financial costs of stacking FCs. Obviously, as the FC's power increases, they will have a greater range and replace classic automobiles. However, it is extremely important to raise energy efficiency to a higher level and minimize the issues of FC systems.

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