Proton Exchange Membrane (PEM) and Solid Oxide (SOFC) Fuel Cell Based Vehicles-a Review

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Abstract–**Interests in clean energy technologies have been growing in recent years especially for transportation, portable equipments as well as stationary power applications. Among the clean technology that gained high attention and investment to date is fuel cell, as a fuel cells is known to be able to produce electricity from a wide selection of fuels such as biogas, natural gas, propane, methanol, hydrogen as well as diesel. In order to contribute to the development of this particular clean energy, we review types of fuel cell particularly in transportation application to date and discuss the challenges for sustainable Fuel Cells Vehicles (FCVs) in future development. In this review paper, we also reviewed the development of FCVs of PEM and SOFC based, specifically. Although much progress has been done for PEM based vehicles thus far, the gas contamination is still a known bottleneck. As for SOFC, there is a lot more room to be improved in order to adopt this type of fuel cell in vehicle such as long time start-up time, insulation and heat dispersion. Nonetheless, SOFC has attained significant interests because it have zero emissions of pollutants to the environment and have high efficiency. Also, having high temperature operation offers many advantages, such as flexibility of using various fuels, high electrochemical reaction rate, and tolerance for impurities. In addition, using ceramics as its electrolyte can reduces the cost of manufacturing.**

Keywords-hydrogen fuel cell vehicle ; PEMFC in vehicles; SOFC in vehicles

I. INTRODUCTION

A fuel cell is well known to be a device that can produce electricity merely via chemical reaction. It is well known to be a useful resource that could take abundant element in the earth and convert it into any sort of power such as electricity, heat as well as water without producing any pollution. One significant difference of fuel cells compared to other clean energy devices is that they produce electricity with almost zero-pollution since the hydrogen and oxygen deployed as reactant eventually combines to form a harmless end product, which is water [1].

Scientists, researchers, inventors and developers all have designed and developed many different kinds and sizes of fuel cells aiming for greater efficiency, and the technical details of each kind vary [1]. However, many of the fuel cell investor and developers are severely restricted by the choice of electrolyte. The design of electrodes, and the materials used to depend on the electrolyte. Today, the common electrolyte types are alkali [2], molten carbonate [3], phosphoric acid [4], proton exchange membrane (PEM) [5] and solid oxide [6]. The first three are liquid type electrolytes and the last two are solid type [1]. As a new type of clean energy device, the advantages of fuel cells such as high efficiency, quiet, environmentally friendly, and simple structure, make it have a very broad application stationary [7], portable equipment [8] and transportation [9].

In transportation, commercial fuel cell vehicles (FCVs) are currently under development in automotive industries. This is as a result of that, fuel cell vehicles are highly-efficient, have very low gas emissions or almost zero emission, and can be powered by hydrogen fuel which can be produced domestically. Thus, FCVs will help achieve environmental, public health, and energy security goal, globally [10].

To date, there are two most popular clean energy alternative approaches that are battery-powered Electric Vehicles (EVs) and Hybrid Electric Vehicles (HEVs), which are already commercialized. However, these two technologies is not preferred by industries due to the following reasons:

a. Battery-powered EVs
   i. The high initial cost, long charging (refueling) time , short driving range, reduced passenger and cargo spaces have proved to be a limitation of battery-powered EVs [11], [12].
b. HEVs were developed to overcome the disadvantages of Internal Combustion Engine (ICE) vehicles and the battery-powered EVs. [11]-[12]. Yet, the development of this technology is limited by:
   ii. The high cost due to usage of motors
   iii. Energy storage system (ESS) issue. ESS of HEVs demanded higher peak power while maintaining high energy density. A hybrid ESS required of batteries, Ultracapacitors (Cs), and/or fuel cells (FCs). These could be a complex option for advanced hybrid vehicle ESS. Hence, this multiple energy storage system is quite a matter.
   iv. Issues related to warranty and reliability due to the lack of manpower in car workshops

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v. Safety concerns due to the usage of high voltage (about 650 V) motors/generators in the vehicle system.

vi. Electromagnetic interference caused by high-frequency and high-current whenever switching in the electric powertrain system [12]. There is recent studies show that there is a cancer risk imposed due to extremely low frequency (ELF) electromagnetic radiation or magnetic field emitted [13-14].

So far, there are two types of fuel cell adapted in vehicles that are PEM [5] and SOFC [6]. This paper reviews these two technologies in terms of operations and the advantages and disadvantages of each fuel cell technology.

II. TECHNOLOGIES OF FUEL CELL VEHICLES (FCVS)

FCVs are basically a combination of automotive engineering, electrical engineering, and fuel cell engineering [15]. FCV is powered by an assembly of single fuel cells, known as a fuel cell stack. This fuel cell stack is engineered to hold few single cells to supply the necessary power for the vehicle. Similar to a combustion engine, a fuel cell stack generates power as long as the fuel is available. The electricity produced by the fuel cell stack drives the electric motor that powers the vehicle [16].

Figure 1 shows the mechanism of FCV produces electricity to drive the car and how compressed hydrogen is supplied to a fuel cell stack [16].

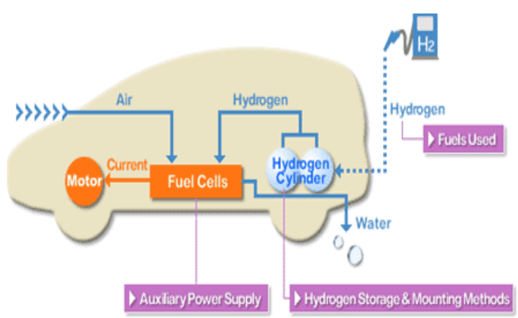

Figure 1. Mechanism of a fuel cell in vehicle [17].

a. Hydrogen Storage & Mounting Methods

i. High-pressure hydrogen tank
High compressed hydrogen gas in low-temperature is stored in a special high-pressure and heat-insulating tank which mounted on the vehicle.

ii. Hydrogen absorbing alloy
Hydrogen is absorbed into a special alloy which is also mounted on the vehicle and is retrieved from this alloy by heating [17].

FCV technology normally use PEM types of fuel cell. For the reason that having low temperature operation and faster response, PEM is generally regarded as the fuel cell of choice used for automotive propulsion applications [18].

Figure 2 shows that each fuel cell is basically composed of an anode, a cathode as well as a proton exchange membrane (PEM). PEM is sandwiched in between electrodes, while the hydrogen enters into the anode side of the fuel cell. This hydrogen is coming from a tank onboard the vehicle. Oxygen, contained in air, enter the cathode side. A catalyst forces hydrogen molecule to split into electron and proton. The proton moves through the membrane and the electron follows an external circuit hence delivering current to the electric motor and other vehicle components. The proton and electron join again at the cathode side, and then recombine with oxygen to form water molecules [18].

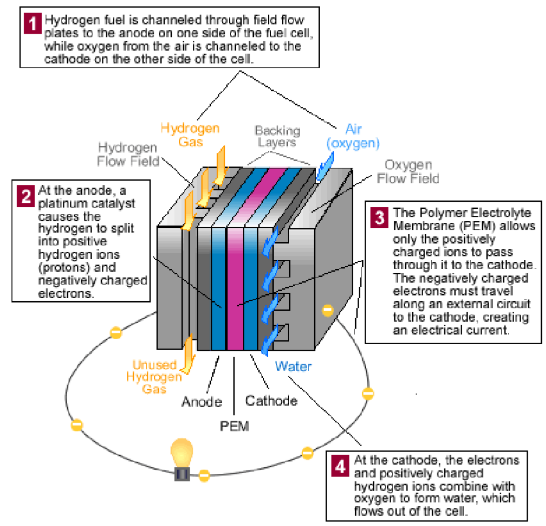

Figure 2. PEMFC Basic Operation [7].

As PEMFC is operate at the lowest temperatures of all fuel cell systems, which give them two big advantages: they are more inexpensive due to a lack of thermal-resilient materials needed, and they take up less room since they don't require insulators or heat dissipation systems. These two factors make them the most commercially viable for the mass market.

However, fuel cell stack, air & fuel control, thermal & water management and uncontaminated fuel supply (requires pure hydrogen) are major trial in the development of the PEMFC technology for use in fuel cells vehicles applications [19]. The issues with air supply system can strongly affected the overall system efficiency.

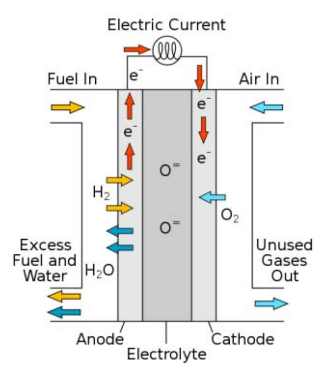

Figure 3. SOFC Basic Operation in automotive application [20].

Recently there has been some interest in using SOFC for propulsion applications in automotive applications [20].Each cell of an SOFC consists of an anode and a cathode with an electrolyte in between. Air is supplied to the cathode side and fuel to the anode side. At the cathode, oxygen is reduced to oxygen ions. These ions diffuse through the electrolyte to the anode side where they electrochemically oxidize the fuel. The by-products of this reaction are electrons, which pass through a circuit to produce electricity and water (if the fuel used is pure hydrogen) [20]. SOFC distinguishes itself among other fuel cell types by the use ceramic electrolyte, which reduces the cost of manufacturing.

SOFCs can work with a different kind of fuels, such as hydrogen, carbon monoxide, methane and also the combinations of these. Fuels with longer carbon chains are possible, with pre-reforming outside the anode [20, 21]. Oxygen is reduced at the cathode. The oxygen ions are transferred through the electrolyte, but the electrons are prevented from passing through the electrolyte [22]. Table 1 shows the comparison between PEMFC and SOFC technologies.

III. Challenges and Limitations for Sustainable Fuel Cells Vehicles (FCVs)

There are some issues related to FCVs, namely the availability of FCVs worldwide, the facility of refueling, storage of hydrogen, the cost production and transportation of hydrogen and safety on-off roads.

- Availability

Most automakers have plan to introduce FCVs to the commercial market in the 2015-2017 timeframe. It was predicted that, by 2020, automakers expect to manufacture tens thousands units of FCVs. As of today, about 300 units of FCVs have been filled at public and private hydrogen stations [15].

Toyota has launched their first commercial hydrogen car using PEMFC as “Mirai: The Future". Hydrogen fuel cell vehicles run for up to 650 kilometers on a full tank.

- Efficiency of the System

FCV requires production, transportation as well as the condensation of hydrogen gas. These processes are demanded for a high cost as well as energy-intensive.

Nevertheless, fuel cells can generate electricity efficiently from a number of fuels and hydrogen can be produces from a number of diverse domestic resources, including biogas [24], natural gas [25], propane [26], methanol [27], and renewable resources like water, using electrolysis [10].

- Safety

It is ensured that automotive manufacturers are committed to build FCVs that are as safe as or safer than that of conventional vehicles by meeting the standards set by the Society of Automotive Engineers and other standard development organizations. FCVs have crucial safety systems designed to protect users in case of an accident [11, 28].

It also similar in the case of the risk of the fuel cell stack and high-voltage battery pack in FCEVs and based on FCVs which produced so far, this components pose no additional risks. Both the fuel cell stack and battery pack are electrically insulated from the vehicle’s metal body and are sealed separately in metal cases. In case of safety regarding high voltage hazards, there are a number of safety systems designed into the vehicle to prevent high voltage hazards and high-voltage circuits are also batch with orange color-coded and posted together with warnings to advice of their presence [29].

For FCVs, hydrogen fuel is stored at high pressures (up to 70 MPa, 10,000psi) in tanks which is much stronger than typical gasoline fuel tank in ICE car. In case of rupture or suddenly burst, the hydrogen storage tanks are designed to withstand twice the maximum pressure to avoid this kind of mishap. The tanks undergo extreme and strict testing to make sure the safety of the vehicle under severe conditions to meet the safety standards for crash safety. Sensors are located throughout the vehicle and, accordingly to the safety systems, to ensure that the driver and the vehicle are safe in the event of a hydrogen leak during the accident [30].

TABLE I. Comparison of Using PEMFC and SOFC Technologies in FCVs

Comparison between PEMFC and SOFC		
	PEMFC	SOFC
Advantages	1-High efficiency 2- Fuel flexibility 3- Smaller and less expensive than materials required for SOFC	1-Can use CO + hydrogen as fuel without any issues 2-Current technology can produces cheaper and lighter insulators (ceramics) 3- Better thermal management
Disadvantages	1- Requirement of pure hydrogen with no CO which technically challenging, complex and expensive. 2- Complex water and thermal management	1- Long start-up times of SOFC systems 2-Insulation and heat dispersion

IV. Conclusion

Here, we reviewed the development of FCVs of PEM and SOFC based. Although much progress has been done for PEM based vehicles thus far, the gas contamination is still a bottleneck. As for SOFC, there is a lot more room to be improved in order to adopt this type of fuel cell in vehicle such as long time start-up time, insulation and heat dispersion. Nonetheless, SOFC has attained significant interests because it have zero emissions of pollutants to the environment and have high efficiency as well. Also, having high temperature operation offers many advantages, such as flexibility of using various fuels, high electrochemical reaction rate, and tolerance for impurities. In addition, using ceramics as its electrolyte can reduces the cost of manufacturing and with better thermal management system, SOFC may outpace PEMs, especial in markets where pure hydrogen is hard to come by.

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REFERENCES

[1] The Basic of Fuel Cell, Smithsonian National Museum of American History Behring Center, Smithsonian Institute. Retrieved on 16th June 2017 via http://americanhistory.si.edu/fuelcells/basics.htm/

[2] Huang, C.Y., Lin, J.S., Pan, W.H., Shih, C.M., Liu, Y.L. and Lue, S.J., 2016. Alkaline direct ethanol fuel cell performance using alkali-impregnated polyvinyl alcohol/functionalized carbon nano-tube solid electrolytes. Journal of Power Sources, 303, pp.267-277

[3] Lanzini, A., Madi, H., Chiodo, V., Papurello, D., Maisano, S. and Santarelli, M., 2017. Dealing with fuel contaminants in biogas-fed solid oxide fuel cell (SOFC) and molten carbonate fuel cell (MCFC) plants: Degradation of catalytic and electro-catalytic active surfaces and related gas purification methods. Progress in Energy and Combustion Science, 61, pp.150-188.

[4] Celik, M., Genc, G., Elden, G. and Yapici, H., 2016. The effect of porosity on performance of phosphoric acid doped polybenzimidazole polymer electrolyte membrane fuel cell. In EPJ Web of Conferences (Vol. 114, p. 02010). EDP Sciences.

[5] Parnian, M.J., Rowshanzamir, S. and Gashoul, F., 2017. Comprehensive investigation of physicochemical and electrochemical properties of sulfonated poly (ether ether ketone) membranes with different degrees of sulfonation for proton exchange membrane fuel cell applications. Energy, 125, pp.614-628.

[6] Fergus, J., Hui, R., Li, X., Wilkinson, D.P. and Zhang, J. eds., 2016. Solid oxide fuel cells: materials properties and performance. CRC press.

[7] Hamelin, J., Agbossou, K., Laperriere, A., Laurencelle, F. and Bose, T.K., 2001. Dynamic behavior of a PEM fuel cell stack for stationary applications. International Journal of Hydrogen Energy, 26(6), pp.625-629.

[8] Dyer, C.K., 2002. Fuel cells for portable applications. Fuel Cells Bulletin, 2002(3), pp.8-9.

[9] Krumpelt, M., Krause, T.R., Carter, J.D., Kopasz, J.P. and Ahmed, S., 2002. Fuel processing for fuel cell systems in transportation and portable power applications. Catalysis today, 77(1), pp.3-16.

[10] Garland, N.L., Papageorgopoulos, D.C. and Stanford, J.M., 2012. Hydrogen and fuel cell technology: Progress, challenges, and future directions. Energy Procedia, 28, pp.2-11.

[11] Chan, C.C., 2007. The state of the art of electric, hybrid, and fuel cell vehicles. Proceedings of the IEEE, 95(4), pp.704-718.

[12] Hannan, M.A., Hoque, M.M., Mohamed, A. and Ayob, A., 2017. Review of energy storage systems for electric vehicle applications: Issues and challenges. Renewable and Sustainable Energy Reviews, 69, pp.771-789.

[13] Jeffers, D. (1996) 'Electric and magnetic fields and health', Structural Survey, 14(1), pp. 4–8. doi: 10.1108/02630809610116188.

[14] Zamanian, a and Hardiman, C. (2005) 'Electromagnetic radiation and human health: A review of sources and effects', EMR & Human Health, 16(July), pp. 16–26. Available at: http://diyhpl.us/~nmz787/biological radio research/Electromagnetic Radiation and Human Health__A Review of Sources and Effects__Fluor Corporation.pdf.

[15] Canis, B., Pirog, R. and Yacobucci, B.D., 2014. Natural Gas for Cars and Trucks: Options and Challenges. Congressional Research Service, November, 19.

[16] May, J. W. and Mattila, M., 2009. Plugging in: A stakeholder investment guide for public electric-vehicle charging infrastructure. Rocky Mountain Institute.

[17] "Mechanism of FCV by Japan Hydrogen & Fuel Cell (2010) http://www.jari.or.jp/Portals/0/jhfc/e/beginner/about_fcv/index.html/ Japan Hydrogen & Fuel Cell Demonstration Project.

[18] Wittstock, R., Pehlken, A. and Wark, M., 2016. Challenges in Automotive Fuel Cells Recycling. Recycling, 1(3), pp.343-364.

[19] SHETTY, A.G., A ProjectReport on "HYDROGEN FUEL CELL VEHICLE" (Doctoral dissertation, Indian Institute of Science).

[20] Sharaf, O.Z. and Orhan, M.F., 2014. An overview of fuel cell technology: Fundamentals and applications. Renewable and Sustainable Energy Reviews, 32, pp.810-853.

[21] Milliner, J. and Roberts, R., 2012. Analysis of Solid Oxide Fuel Cell-Gas-Turbine Hybrid System Technology for use in Aircraft. Explorations–The Journal of Undergraduate Research, Scholarship and Creativity at Wright State, 1(1), p.10.

[22] Ivers-Tiffée, E., Weber, A. and Herbstritt, D., 2001. Materials and technologies for SOFC-components. Journal of the European Ceramic Society, 21(10), pp.1805-1811.

[23] Curtin, S. and Gangi, J., 2015. The Business Case for Fuel Cells 2015: Powering Corporate Sustainability. Fuel Cell and Hydrogen Energy Association.

[24] Alves, H.J., Junior, C.B., Niklevicz, R.R., Frigo, E.P., Frigo, M.S. and Coimbra-Araújo, C.H., 2013. Overview of hydrogen production technologies from biogas and the applications in fuel cells. international journal of hydrogen energy, 38(13), pp.5215-5225.

[25] Dicks, A.L., 1996. Hydrogen generation from natural gas for the fuel cell systems of tomorrow. Journal of power sources, 61(1-2), pp.113-124.

[26] Zhan, Z., Liu, J. and Barnett, S.A., 2004. Operation of anode-supported solid oxide fuel cells on propane–air fuel mixtures. applied catalysis A: general, 262(2), pp.255-259.

[27] Kreuer, K.D., 2001. On the development of proton conducting polymer membranes for hydrogen and methanol fuel cells. Journal of membrane science, 185(1), pp.29-39.

[28] Ehsani, M., Gao, Y. and Emadi, A., 2009. Modern electric, hybrid electric, and fuel cell vehicles: fundamentals, theory, and design. CRC press.

[29] Chan, C.C. and Chau, K.T., 2001. Modern electric vehicle technology (Vol. 47). Oxford University Press on Demand.

[30] Goswami, D.Y. and Kreith, F. eds., 2007. Energy conversion. CRC press.