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FUEL CELLS FOR MOBILE APPLICATIONS

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Abstract

Fuel cells (FCs) are electrochemical devices, which produce electricity (and sometimes heat) without any intermediate step. These units are known for their high total and electrical efficiency, low emission levels, silent operations and scalability. There are several types of fuel cells, which operate at different temperatures, require different fuels and levels of servicing. Some of FC types can be also used for mobile applications – e.g. Unmanned Aerial Vehicles (UAV). Auxiliary Power Units (APU) or main power source is for FC vehicles. Recently, there has been a growing interest in research on mobile applications of fuel cells, both for civilian and military purposes. Several commercial companies focusing on fuel cells have been established, performing their R&D activities in their niches. In addition, there are special dedicated research funds for fuel cell and hydrogen research in countries such as USA, China, Japan, France and Germany. Moreover, the European Commission devotes funds for the fuel cell activities through a public-private partnership. This trend is predicted to continue in coming years, as fuel cells become smaller, easier and cheaper to operate and manufacture. This paper focuses on the current "state of the art" in fuel cell research, both commercial and governmental/military. In addition, some examples of mobile applications, focusing on fuel cell vehicles, spacecrafts and UAVs are presented, together with a predicted outcome for following years.

Keywords: *fuel cells, mobile application, PEM, SOFC, market introduction*

1. Introduction

Fuel cells (FCs) are electrochemical devices, which produce electricity (and sometimes heat) without any intermediate step. These units are known for their high total and electrical efficiency (even above 60% of electrical efficiency), low emission levels (especially nitrogen and sulphur oxides), silent operations and scalability. There are several types of fuel cells, which operate at different temperatures, require different fuels and levels of servicing. Among them, the low-temperature Polymer Electrolyte Membrane Fuel Cells (PEM FC) are probably closest to the mass-market entry. Other type, like the high-temperature Solid Oxide Fuel Cell (SOFC), can exhibit more advantageous performance for certain applications, however more research is required before the wide spread use.

Many types of fuel cells can be used for mobile applications - from UAVs, through APU, up to main power sources for FC vehicles and spacecrafts. Over last years, there has been a growing interest in research on mobile applications of fuel cells, both for civilian and military purposes. During this time several commercial companies focusing on fuel cells have been established, which develop technologies in their niches. In addition, there are special dedicated research funds for fuel cell research in countries such as USA, China, Japan, France and Germany. Moreover, the European Commission devotes funds for the fuel cell activities under the Fuel Cell and Hydrogen Joint Undertaking (FCH JU) topic. This trend is predicted to continue in this and next decade, as fuel cells become smaller, easier and cheaper to operate and manufacture.

On the other hand, fuel cells are still very expensive to manufacture and operate. For example, the typical lifetime of a FC system is still shorter than the traditional counterparts (e.g. Diesel engine) and thus the corresponding degradation rate of performance is faster. Also, some FC types use expensive catalysts while other requires very demanding conditions. These are the research topics of current projects around the world and over recent few years, significant scientific and engineering goals have been achieved.

Several FC types have the potential to enter several mobile application niches, especially in the military field. Some FC mobile systems might enter the mass market before the end of this decade. However, more wide spread introduction of FC technologies might be hindered by the lack of proper infrastructure, especially in case of hydrogen for FC vehicles.

2. Fuel cell types

The term fuel cell (FC) denotes a diverse group of electrochemical devices, known for their high electrical efficiency. There are several types of FC, which operate at different temperatures, require different fuel and operating modes. These different types of FC can operate as portable devices, through mobile and space applications, up to intermediate and large stationary power units. Although FCs are known for a long time, only recently has widespread research on fuel cells have been initiated. Currently, most fuel cell types are still at the research level of investigation, although some commercialisation has been made – there are several companies offering their products on the market. Tab. 1 lists the most important features of several main types of FCs. Perhaps the most advanced are the PEM FC, which are commercially produced and utilised in many different versions and around the World. As of 2012, the PEM FC are probably closest to the mass-market entry. However, the PEM FC requires expensive catalysts, such as platinum or rhodium. In addition, the PEM FC requires hydrogen as a fuel, which either has to be supplied by the infrastructure or produced in the system by a costly reformer. The problem of infrastructure is explained in greater detail in point 4.1. of this paper.

Other types, such as SOFC or Molten Carbonate Fuel Cell (MCFC) do not require expensive catalysts and their operating parameters are probably wider, but might be at a lower development stage, although recently a significant improvement has been noticed. This leads to an overall conclusion that several FC types might be close to or at the "early market" stage before the end of this decade, if satisfactory results are achieved by the research groups.

3. Fuel cell for mobile applications

General requirements for mobile FCs in comparison to stationary devices are presented in Tab. 2. The mobile FC system usually is smaller in size with lower weight. These two factors are important for mobile applications, especially for the aerospace sector, where the mass budget has usually high constraints.

On the other hand, the mobile FC systems require higher level of autonomy, to ensure proper and constant performance during operations, especially when they are used as independent units (such as UAVs).

Most FC systems for mobile applications are based on the PEM FC, as the start-up of this type of FC is fast. This is one of main requirements for a FC vehicle, where the FC systems is the main power unit. On the other hand, although other systems, such as high temperature SOFC, require more time for start-up, but in some cases a longer start-up time might be acceptable. For example, in case of mobile system, which after being turn on is to operate constantly for 24 hours or more, one hour of start-up time might be acceptable.

4. FC mobile products

Over recent years, several mobile FC systems were introduced to the market. The most visible examples are the FC automobiles, FC spacecrafts and FC UAVs. The most known examples are within the FC vehicles for personal transportation.

Tab. 1. Comparison of four different types of fuel cells

Parameters	PEMFC (Proton Exchange Membrane Fuel Cell)	AFC (Alkaline Fuel Cell)	SOFC (Solid Oxide Fuel Cell)	DMFC (Direct Methanol Fuel Cell)
Electrolyte	Polymer membrane	Liquid solution of KOH	Dense ceramic ionic conductor (e.g. YSZ, CGO, ScSZ)	Polymer membrane
Operating temperature	50-180°C	50-200°C	450-1000°C	60-200°C
Anode reaction	$H_2 \rightarrow 2H^+ + 2e^-$	$H_2 + 2OH^- \rightarrow$ $\rightarrow 2H_2O + 2e^-$	e.g. $H_2 + O^{2-} \rightarrow$ $H_2O + 2e^-$	$CH_3OH + H_2O \rightarrow$ $\rightarrow 6H^+ + 6e^- + CO_2$
Cathode reaction	$½O_2 + 2H^+ + 2e^- \rightarrow$ $\rightarrow H_2O$	$½O_2 + H_2O + 2e^- \rightarrow$ $\rightarrow 2OH^-$	$½O_2 + 2e^- \rightarrow O^{2-}$	$3O_2 + 12H^+ + 12e^- \rightarrow$ $6H_2O$
Fuel	Pure H_2	Pure H_2	H_2, NH_3, CO, CH_4, other hydrocarbons	CH_3OH
Oxidant	Oxygen, air	Oxygen, air	Oxygen, air	Oxygen, air
Efficiency (electr.)	30-60 %	ca 50%	45-65%	30-50%
Cogeneration	Yes	Yes (space)	Yes	–
Reformer required	Yes	Yes	No	No
Examples of application	transportation, APU, emergency backup, residential, military applications	some space applications, transportation, portable power units	cogeneration, power plants, residential sources, transportation, small applications	replacement of batteries (mobile devices), small military applications
Advantages	quick start up, non-corrosive electrolyte, high power output	relatively inexpensive, quick start up	no expensive catalysts required, some degree of fuel flexibility, high power output, relative simplicity of design	no fuel reformer required, reduces complication and cost
Drawbacks	use of expensive catalysts, very sensitive to fuel impurities (CO), reformer and humidifier required	sensitive to fuel impurities, use of expensive catalysts	longer start up time, high temperature of operation, sensitive to sulphur poisoning, carbon deposition, high fabrication cost	lower efficiency and power density, limiting applications,

Tab. 2. Comparison mobile and stationary FC system requirements

Parameter	Mobile FC system	Stationary FC system
Mass	Constrained	Generally unconstrained
Size	Limited to very limited, often also geometrical constraints	Usually unconstrained
Power output	From few We to 100 kWe	Up to > MWe scale
Servicing	Greater degree of autonomy, servicing usually between operations	Servicing also possible during operations
Durability	Lower (e.g. 5000 hours)	Higher (>20000 hours)
Start-up, turn-off	Required, fast and frequent	Slower, less frequent or continuous operations only
Atmospheric conditions	Varying, also under rain, sub-zero and high temperatures	Usually (but not always) under at least semi-controlled conditions (e.g. inside a building)
Cost per installed/ produced unit of power	Higher	Lower
Additional components	Smaller, less durable, more expensive	Bigger, oriented towards durability and cost

Perhaps the best example of personal transportation FC automobile is the Honda FCX Clarity, which since 2008 is under limited production. Another FC vehicle, the Mercedes B-Class F-Cell, is since 2011 offered for lease. The main market for these cars is American state of California, where some hydrogen filling stations were built and more are planned. In Germany, a network of hydrogen stations is also being built.

In addition, several other well-known producers from the automobile industry, such as Toyota, GM, Hyundai, KIA or Renault as well as some other smaller companies, presented their concept or demonstration vehicles and were claiming interest in FC automobiles. Moreover, according to official press releases, both Mercedes and Honda plan to introduce their FC vehicles into the market before the end of this decade.

Fig.1. Honda's FCX Clarity hydrogen tank inlet

In the field of space exploration, FCs were installed on multiple spacecrafts and likely in the future more applications for this sector will be found. Although most satellites and space vehicles rely on solar panels and batteries, sometimes FCs are used in order to save the mass and provide higher power output. Between 1981 and 2011, the NASA's Space Shuttle (STS) used the AFC to produce 21 kWe of power – far more than any reasonably-sized solar panels could provide. This FC type operated on hydrogen and oxygen, producing electricity, heat and portable water for astronauts.

The biggest drawback for the FC in spacecrafts is that this power source requires fuel and oxidiser, which adds to the mass budget and can limit the mission. That is why for most applications it is better to use solar panels, which exhibit much lower electrical efficiency (i.e. ca. 10-20%), but in comparison with FC do not require tanks for fuel and oxidiser. However, with rising power requirements for satellites (especially the telecommunication ones, located at the geostationary orbit), estimated to reach even 30 kWe, regenerative and closed-loop FC systems might be introduced. Several companies and scientific institutions from around the World investigate the concept of regenerative FC for spacecrafts, mostly focusing on the PEM FC. Such regenerative FC systems should operate for 15 or more years and undergo as much as 1300 charging cycles.

In the field of FC UAVs, the work focuses mostly on demonstration of flight endurance and ability to service the vehicle away from the main base. Significant part of research in this topic is done by or with the military from many countries around the World. The most popular system for UAVs is the PEM FC and the current "state of the art" results claim over 26 hours of continuous flight operations, which can be over seven times more than in case of batteries.

In case of UAVs, some experiments are done also with the SOFC. The choice of SOFC as a power unit gives an advantage during field operations, as this type of FC can run on available traditional fuels (e.g. low-sulphur JP-8 or LPG), with no or less reforming. This fact can reduce the complexity of FC operations, especially in remote areas.

An example of demonstration-stage SOFC system for UAV is the ROAMIO S245X power unit. This device is intended to be used for small UAV (less than 4 meters of wingspan). The autonomy of flight is expected to be at least 8 hours. The SOFC power unit is also smaller and lighter than the battery pack, which allows for more instruments to be installed onboard the UAV. Over 40 units of the ROAMIO D245X were recently supplied to various US Army organisations. The ROAMIO D245X unit delivers 245 We, weights 2.6 kg and consumes 112 grams of propane per hour of operations.

Finally, the FC units can serve for mobile applications as APU devices. Some recent examples include APU for big-size trucks and airplanes. In this case, often the SOFC are being investigated for these applications due to their multi-fuel capability.

4.1. The infrastructure problem

With more widespread introduction of FC vehicles, the lack of infrastructure might be perhaps the most difficult factor to overcome. Vehicles using the PEM FC require hydrogen, which has to be produced and delivered to the "hydrogen gas stations". However, so far, most of hydrogen is currently produced from hydrocarbons and its mass storage is not a trivial task. There are no large-scale pipelines, which transport the hydrogen from refineries to hydrogen stations, which is an uneasy task on a mass scale. Clearly, the introduction of hydrogen technologies to the mobile segment will require significant investment on the infrastructure.

In previous decade, there were several attempts to build local hydrogen infrastructures, which would serve FC vehicles. The most known example is the state of California, where hydrogen stations are being introduced since 2005. As of March 2012, there were 37 hydrogen stations, mostly around Los Angeles, listed as operational, funded or demonstration plants. However, recently there are no announcements for new hydrogen stations in California. At the same time in Europe, there have been two major attempts to establish hydrogen networks. The first one was created in south-western Scandinavia – in Sweden, Denmark and Norway under the Scandinavian Hydrogen Highway Partnership. More than 25 hydrogen stations were planned to be built around south-western Scandinavia and some of them became operational between 2006 and 2009. However, this Partnership is now experiencing some difficulties, as the main hydrogen supplier decided to close or sell to other companies all Norwegian hydrogen stations by the end of 2012 due to cost issues.

The German plans seem to be more ambitious – around 50 hydrogen stations are planned to be built before 2015. So far, there have been no announcements of cancellation or delays. Currently, 15 hydrogen stations are functioning in Germany.

Fig. 2. An Electric Vehicle (right), charged from a stationary "early market" commercial SOFC power unit (middle). This SOFC also "transfers" the waste heat to the domestic water tank (left)

It is quite possible that FC will be used for smaller, niche mobile applications before the more widespread applications. For example, FC vehicles could be used on a small island or urban location, where the cost of infrastructure deployment as well as number of vehicles and their expected daily range would be low.

It is important to note that recently the attention might have shifted towards electric vehicles (EVs), as the completely charging infrastructure (i.e. the electricity grid) is available and research on batteries resulted in major improvements. Thus, it might be possible that over next several years a "competition" between EV and FC vehicles will be observed, each securing first their own niches. Currently, it is predicted that EVs might become widespread as an urban transportation method, whereas hybrid, FC and traditional vehicles could compete on long-range segment of transportation. Finally, it is important to note that some stationary FC systems might also serve to mobile applications utilising batteries, perhaps together with renewable energy sources. In such a configuration, the FC system would be located at a parking/servicing point for an electric battery – driven mobile system and serve as a charger. This concept has been already demonstrated with interesting results.

4.2. The Fuel Cells and Hydrogen Joint Undertaking

The widespread introduction of FC mobile technologies is related to the cost of FC units and their durability. So far, the FC mobile units can be several orders of magnitude more expensive than their traditional counterparts. Currently, the cost of mobile traditional engine (e.g. Diesel engine) is not higher than 25-35$ per kW. At the same time, the mobile FC system can cost several thousand $ per kW or more. In order to compete with traditional power systems, the mobile FC units have to be cheaper, which means mass production, simplified fabrication methods, lower amount of catalysts and/or reforming systems and greater durability. These two problems are addressed in many research projects, also by the European Commission (EC).

The Fuel Cells and Hydrogen Joint Undertaking (FCH JU) is a pan-European public-private venture, which aims to develop technologies related to FC and hydrogen. There are three partners in the FCH JU – the European Union, represented by the EC, the New European Research Grouping on Fuel Cells and Hydrogen and the European Industry Grouping for a Fuel Cell and Hydrogen Joint Technology Initiative. FCH JU aims to accelerate market introduction of FC and hydrogen technologies through co-funding the research, technological development, demonstration and supporting activities. The activities cover the entire range of R&D projects – from basic to breakthrough research, through applied studies up to demonstration activities. The FCH JU project are complemented by some cross-cutting activities, such as work on codes, regulations and life cycle, market, education or socio-economic analysis.

The FCH JU activities are performed since 2008 through "open and competitive calls for project proposals". Part of FCH JU activities is related to transportation and refuelling infrastructure projects. For the period between 2008 and 2013 a budget of nearly 1 billion € was allocated to FCH JU, from the EC and industry.

The FCH JU projects are jointly realised by consortia consisting of small and medium enterprises (SME), major industry, academia and research institutions. Up to now, there have been five calls for projects and approximately one hundred projects were or will be funded. Unfortunately, so far no entity from the "new EU member states" has participated in the FCH JU, but in the next years there will be further opportunities to join consortia. At this moment, the work focuses on definition of FCH JU activities under upcoming Horizon 2020 programme.

5. Conclusions

Over next few years, various types of FCs might be introduced to some mobile applications, mostly in niches. Their price per unit of power output will be still higher in comparison to traditional counterparts, but FCs exceptional performance parameters might be the key to mass market introduction. Thus, the durability of FC system might play here a critical role, as together with high efficiency the operating costs of a power unit would be significantly decreased over traditional power sources.

In previous decade there were some attempts to create some local hydrogen networks for FC vehicles. However, probably also due to recent economic environment, some investments have been halted. It is probable that the introduction of FC vehicles and suitable network for them might happen later than in this decade. Thus, the FC vehicles fed by hydrogen might be introduced to the mass market later than into the other mobile FC segments.

At the same time, a growing interest in the power sources for UAVs is observed. Most of the efforts come from the military, which might be the first "mass-scale" user of matured FC technologies. The military users might be less "price per kW"- constrained, but more demanding towards autonomy, remote operations, ease of use and multi-fuel capability. The military UAV niche might be the one, where visible FC presence could be established before the end of this decade.

Another market entry for FC might be done due to the high-temperature FC types, such as SOFC. Since it is easier to store the hydrocarbon fuels rather than hydrogen and the infrastructure already exists, SOFCs might provide several advantages over traditional power sources. On the other hand, significant improvement has to be done on the start-up, if high-temperature FC units are to be used for mobile applications. This goal might be achieved by employing the microtubular geometry of cell unit of SOFC. Such geometry significantly reduces stress and sealing issues, which in turn allows for faster start-up.

Finally, the role of national or pan-national initiatives, such as the FCH JU, might be critical to FC development, especially for the market introduction and cost-sharing of research activities between the industry and governing bodies.

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