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Review

Progress on design and development of polymer electrolyte membrane fuel cell systems for vehicle applications: A review

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ABSTRACT

Due to its merit of rapid start-up, lower pollution and high energy conversion efficiency, polymer electrolyte membrane fuel cell (PEMFC) system has been considered as one of the most promising propulsion system for electric vehicles. Although the development of PEMFC system has been experienced rapid growth for several decades, many challenges still need to be overcome for promoting commercialize fuel cell technology. In order to understand the design concept of PEMFC system and update the development status of fuel cell system for electric vehicle, as well as help fuel cell system developers or electric vehicle manufacturers to improve the performance and durability of fuel cell electric vehicles, the up-to-date technical targets such as power density, operation temperature, dynamic response and lifetime for PEMFC systems in different countries have been summarized and compared in this review. Furthermore, from the aspects of hydrogen management and air management and major degradation mechanisms under various operation conditions, the design status of the system configuration in fuel cell has also been analyzed in detail. Finally, according to the design and intended operation the mitigation strategies have also been proposed to promote the development of PEMFC system for electric vehicle applications.

1. Introduction

Fuel cells can directly convert the chemical energy of diverse fuels into electricity without combustion and have been regarded as the most promising power generation technologies, owing to their high efficient and power density, zero emission, silent operation, high reliability and low maintenance [1, 2]. According to the type of the electrolyte of fuel cells, they can be divided into polymer electrolyte membrane fuel cells (PEMFCs), solid oxide fuel cells (SOFCs) and alkaline membrane fuel cells (AMFCs) and so on. Due to the easy accessibility of hydrogen fuel and the high efficiency of system, PEMFCs have been considered as the most popular energy source of engine for electric vehicles throughout the world. To achieve the commercialization of PEMFCs in electric vehicles, the continuous global research, development and demonstration (RD&D) has gained experience for several decades. For the last 3 years, fuel cell electrical vehicles (FCEVs) have gone through a turning point from laboratory verification to commercial application and some notable milestones are worth mentioning. Among these milestones, it is worth noting that Hyundai and Toyota introduced their FCEVs into market in 2016, and that Honda also launched its new environmentally-friendly hydrogen-powered FCEVs into market at the end of 2016. Others companies, such as Daimler, General Motor and Nissan, are reportedly set to begin commercialization before 2020.

For occupying the commanding height of FCEVs, many fuel cell research projects about the innovation of FCEVs technology have been issued the documents on the technical targets and specification requirements for FECVs in different organizations and countries. These documents refer to the Fuel Cell Projects from Department of Energy (DOE) [3] in U.S., the Fuel Cell Programs from New Energy and Industrial Technology Development Organization (NEDO) [4] in Japan, European Hydrogen and Fuel Cell Technology Platform (HFP) [5], and New Energy Vehicles Program from Chinese 13th five-year plan [6].

Actually, PEMFCs system, as the core part of FCEVs, determines the performance and durability of FCEVs. It is well known that PEMFCs system is composed of hydrogen, air and thermal management subsystem. The basic performance and function of these three subsystems is

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the cornerstone of the design of power train configuration and architecture of FCEVs. For further promote the development of PEMFCs for electric vehicles, this review will summarize the technical targets for the fuel cell system in U.S., Japan, the European Union, and China in the first section. And then, the up-to-date design of the fuel cell system for transportation application, including the research progress of hydrogen, air and thermal management subsystem, system strategies related to durability and fuel cell system integration, will been discussed in the next section. The benchmark studies of fuel cell system configuration with respect to various concepts provided by FCEVs manufactures will been analyzed in the last section.

2. Technical targets for fuel cell systems in different countries

To meet market requirement, the operational performance of FCEVs, such as the driving range with a full tank of gas, acceleration (< 10 s from 0 to100 km per hour), rapid cold-start (< 30 s from −30 °C) and 5000 hours lifetime, should be similar to or even better than that of internal combustion engine (ICE) powered vehicles. For this reason, U.S., Japan, the European Union and China have proposed their own technical targets for the development of fuel cell systems for electric vehicles for next 5 years, including power density, system efficiency, transient operation performance, cold-start ability and cost et al., as shown in Table 1.

2.1. US Department of Energy Fuel Cells Program

Hydrogen, Fuel Cells, and Infrastructure Technologies (HFCIT) Program proposed by the U.S. DOE Office of Energy Efficiency and Renewable Energy [3] is beneficial for facilitating the development of fuel cell technologies [7]. On the basis of the R&D status of national laboratories, universities and industry partners, the U.S. DOE Fuel Cells Program updates the technical targets for integrated transportation fuel cell power systems [8]. As listed in Table 1 (the critical technical targets in 2016 from DOET), the energy efficiency of fuel cell systems is above 50%, higher than that of ICEs. Moreover, it is necessary to set up a technical target for fuel cell system net efficiency to achieve a long driving distance with a fuel tank of hydrogen. It is calculated as the ratio of DC output energy (E_{DC}) to the lower heating value of input hydrogen (Q_{H2}) as represented by the following equation:

$$\eta_{fcs} = \frac{E_{DC}}{Q_{H2}} \tag{1}$$

Additionally, because fuel cell system is composed of fuel cell stack and corresponding balance-of-plant (BOP), the additional fuel loss will be caused by purging and other operation during the running process of fuel cell system. For this reason, the fuel cell system efficiency can be calculated by:

Table 1
Technical targets of integrated transportation fuel cell power systems operating on direct hydrogen from DOE, NEDO, FCU JU and MOST in U.S., Japan, Europe and China, respectively.

Characteristic	DOE	NEDO	FCU JU	MOST
Peak power efficiency (%)	65	60	55	55
Rated power efficiency (%)	–	–	40 (NEDC)	50
Power density ($W L^{-1}$)	650	–	–	600
Specific power ($W kg^{-1}$)	650	–	–	–
Cold start-up time (seconds)	30	30	–	–
Cold start-up temperature (°C)	−30	−40	−25	−30
Durability in automotive drive cycle (hours)	5000	5000	5000	5000
Start-up/shutdown durability (cycles)	5000	–	–	–
Top operation temperature (°C)	90	95	–	–
Storage hydrogen pressure (MPa)	70	70	70	70
Cost (/kW)	$ 40	$ 97	€ 100	–

$$\eta_{fcs} = \eta_{stack}\cdot\eta_{BOP}\cdot\eta_{fuel} = \frac{V_{cell}}{1.482}\cdot\frac{E_{net}}{E_{stack}}\cdot\frac{Q_{reaction}}{Q_{reaction}+Q_{purging}} \tag{2}$$

where, V_{cell} and E_{stack} is the average cell voltage and output energy of fuel cell stack, respectively. E_{net} is the output energy of fuel cell system. $Q_{reaction}$ is the amount of hydrogen consumed in electrochemistry reactions and $Q_{purging}$ is the amount of hydrogen purged.

For the practical application of fuel cell system, the driving range of FCEVs is similar to or even longer than that of the traditional vehicle powered by ICE, meaning that the efficiency of fuel cell system is at least as high as 65% of peak efficiency. Simultaneously, the peak efficiency of fuel cell system is < 25% of rated power, combining the stack and BOP efficiency as a function of fuel cell net power, according to the Eqs. (1) or (2). In order to place fuel cell system in front cabin of traditional vehicle platform under hood, the fuel cell system needs to be integrated to obtain power density as high as 650 $W L^{-1}$. Occasionally, FCEVs need to be operated under freeze temperature so that fuel cell systems need to be able to start up at −30 °C in 30 s for providing 50% of rated power. It is can also be obtained from Table 1 that durability is another important factor for hindering the commercialization of FCEVs. Specially, the lifetime targets of U.S. DOE (with dynamic cycling and < 5% of rated power degradation at the end of fuel cell life) for integrated transportation fuel cell systems are 5000 h. The data of 2015 Annual Merit Review report from DOE shows that the lifetime of transportation fuel cell system is 3900 h [3], which is still a gap compared with the ultimate target. Furthermore, the test protocol for the durability of fuel cell systems in automotive drive cycles and start-up/shutdown cycles has also been illustrated in DOE fuel cell program [3].

2.2. Japanese New Energy and Industrial Technology Development Organization Fuel Cell Programs

Since 2005, the Fuel Cell Programs from NEDO [4] promoted the RD &D of PEMFC technology in Japan [9]. The proposed roadmap refers to the technical development themes and targets for each development stage and divides the overall development strategy of fuel cells in Japan into three phases: From 2009 to around 2025 is the phase for expanding fuel cells including residential and stationary fuel cells and FCEVs. The critical objective of this phase is to decrease the cost of fuel cells. From mid-2020s to around 2030 is the phase for building up hydrogen power plant and supply chain. From 2030 to around 2040 is the phase for producing hydrogen by using carbon dioxide (CO_2)-free technique.

For the transportation application of fuel cells, the peak energy efficiency target of NEDO is 60% (as listed in Table 1), which is 5% lower than that of U.S. DOE. It is reported that the peak energy efficiency of Toyota Mirai and Honda Clarity is higher than 60% and that the driving range of Toyota Mirai and Honda Clarity is about 502 and 589 km, respectively. Moreover, the target of NEDO for freeze start-up performance is to start up at −40 °C in 30 s without external heat source, and lifetime targets of NEDO for integrated PEMFCs power systems are as follows: the 2005 target of ~1000 h, the 2010 target of ~3000 h, the 2015 target of ~5000 h [7] and the ultimate target of ~5000 h [4].

2.3. European hydrogen and fuel cell technology platform

The Fuel Cells and Hydrogen Joint Undertaking (FCH JU) is a public private partnership, providing financial support for the research on the technological development and demonstration (RTD) of fuel cell and hydrogen energy technology in the European Union. The main objective of this organization is to accelerate the market introduction of these technologies, realizing their potential as an instrument in achieving carbon-lean energy system [5]. FCH JU has provided several projects for supporting the RD&D of the fuel cell system in the area of transportation application, stationary power and portable power.

As listed in Table 1, the peak power efficiency proposed by FCH JU is at least 55%, which is 5% lower than that proposed by NEDO and