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ScienceDirect

Journal of Power Sources 177 (2008) 167–176

JOURNAL OF POWER SOURCES

www.elsevier.com/locate/jpowsour

Fuel cell systems for transportation: Status and trends

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Received 24 July 2007; received in revised form 5 October 2007; accepted 5 October 2007
Available online 18 October 2007

Abstract

The U.S. program for the development of direct hydrogen-fueled automotive fuel cell systems has established ambitious performance and cost targets for the 2010 and 2015 time frames. These targets include peak and rated power efficiencies of 60% and 50%, respectively, specific power and power densities of 650 We kg^{-1} and 650 We L^{-1}, and manufactured costs of \$45 and 30 kWe^{-1} for 80 kWe^{-1} net systems in the 2010 and 2015 systems, respectively. In this paper, we discuss the use of fuel cell system models to examine the performance and projected manufactured costs of 2005 systems and the improvements needed to meet the 2010 and 2015 system level targets. It appears possible to meet most of the 2010 performance targets with advances such as the nano-structured thin film electrocatalysts and a modified electrolyte membrane capable of operating at up to 95 °C, at least for short periods. To meet the 2015 targets, however, the fuel cell systems may need to operate without pressurization at higher temperatures of up to 120 °C without the need to humidify the fuel gas and air, along with several other improvements in stack and balance-of-plant components. Our simulations provide quantitative estimates of the various performance and cost parameters of the near-term and the advanced systems that can achieve the targets set for automotive fuel cell system development.
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Keywords: Fuel cell systems; Polymer electrolyte membrane; Heat rejection; Water management; Air management; Transportation

1. Introduction

Fuel cells offer many advantages over the internal combustion engines (ICE) for vehicular applications because they are energy efficient, clean, and fuel flexible. Hydrogen fuel cell systems have the potential to reach 60% peak efficiency on lower heating value (LHV) basis. On-board the vehicle, conversion of hydrogen to traction power produces water only. Hydrogen can be produced from a variety of sources including fossil fuels such as natural gas, renewables such as solar and wind power, biomass, and nuclear energy.

Cost and durability are generally regarded as the major challenges to commercialization of fuel cells. Size, weight, and system simplicity are also important to the adoption of fuel cells in light duty vehicles. Fuel cell systems (FCS) must be reduced in cost before they can be competitive with internal combustion engines. The cost of automotive ICEs is currently about \$25–35 kW^{-1}; a fuel cell system needs to cost less than \$50 kW^{-1} for the technology to be competitive [1]. Adequate durability of fuel cell systems under rapidly varying driving conditions has not been established; they need to be as durable and reliable as current internal combustion engines, i.e., 5000 h lifespan (150,000 miles equivalent) and able to function over the full range of ambient conditions (−40 to +40 °C).

Air management for fuel cell systems is a challenge because today's compressor technologies are not ideally suitable for automotive fuel cell applications. In addition, thermal and water management for fuel cells are issues that are not yet fully resolved. Fuel cell operation at lower temperatures creates a small difference between the operating and ambient temperatures, necessitating large heat exchangers [1]. Fuel and air feed streams need to be humidified in a highly controlled manner for proper operation of fuel cells. Whereas having to carry consumable water on-board the vehicle is considered unacceptable, recovering water formed in the fuel cell for humidifying the inlet gases adds to the complexity of the system.

Finally, the size and weight of current fuel cell systems must be further reduced to meet the stringent requirements for automobiles. Size and weight reduction applies not only to the fuel cell stack (catalysts, membranes, gas diffusion media, and bipolar plates) but also to the ancillary components making up the balance of plant [1].

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0378-7753/\$ – see front matter. Published by Elsevier B.V.
doi:10.1016/j.jpowsour.2007.10.026

Table 1
DOE/Freedom CAR technical targets

Direct hydrogen fuel cell power system		Target		
Characteristic	Units	2005	2010	2015
System cost	$ kWe^{-1}	125	45	30
System efficiency @ 25% rated power	%	60	60	60
System efficiency @ rated power	%	50	50	50
System power density, specific power	W L^{-1}, kg^{-1}	500	650	650
Stack cost	$ kWe^{-1}	65	25	15
Stack efficiency @ 25% rated power	%	65	65	65
Stack efficiency @ rated power	%	55	55	55
Stack power density, specific power	W L^{-1}, kg^{-1}	1500	2000	2000
MEA cost	$ kWe^{-1}	50	10	5
MEA performance @ rated power	mW cm^{-2}	600	1000	1000
MEA degradation over lifetime	%	10	10	5
PGM cost	$ kWe^{-1}	40	5	3
PGM content (peak)	g kWe^{-1}	2.7	0.5	0.4
PGM loading (both electrodes)	mg cm^{-2}	0.7	0.3	0.2
Membrane cost	$ m^{-2}	200	20	20
Bipolar plate cost	$ kWe^{-1}		5	3
CEM system cost	$	600	400	200

In this paper, we discuss the status of current fuel cell system technology relative to the DOE/FreedomCAR targets listed in Table 1. The focus of this paper is on identifying the gaps in current technology, and the likely future advancements in technology that may overcome the shortfalls, to enable meeting the listed targets.

2. Near-term fuel cell systems (Argonne 2005 FCS)

Fig. 1 is a schematic of an 80 kWe pressurized FCS configuration (Argonne 2005 FCS) considered as being an idealized representation of the 2005–2006 technology [2]. The polymer electrolyte fuel cell (PEFC) stack in Fig. 1 operates at 2.5 atm at rated power, 80 °C cell temperature, 50% O_2 utilization and 70% per-pass H_2 utilization. The cell MEA consists of anode and cathode catalyst inks deposited onto the gas diffusion layers (GDL), which are hot-press laminated with the 50 μm-thick Nafion membrane. The Pt loading is 0.50 mg cm^{-2} on the cathode and 0.25 mg cm^{-2} on the anode. The flow channels are fabricated from 2 mm-thick expanded graphite plates, with each plate having cooling channels. The air management subsystem consists of a compressor–expander module (CEM) with a liquid-cooled motor, mixed axial and radial flow compressor, variable-nozzle radial inflow turbine, and airfoil bearings. The fuel management subsystem includes a hybrid ejector-hydrogen pump to recirculate a portion of the spent anode gas. The water management subsystem uses an enthalpy wheel humidifier (EWH) for the cathode feed and a membrane humidifier (MH) for the anode feed. At rated power, the feed gases are humidified to 60% relative humidity (at the stack temperature). The system is designed to be water balanced, i.e., only the water produced in the stack is used for humidifying the feed gases. The dual-loop heat rejection subsystem has a high-temperature circuit for supplying coolant at 70 °C to the stack, and a low-temperature circuit for supplying coolant at 55 °C to the vehicle traction motor and the CEM motor. The coolant in both circuits is aqueous ethylene glycol solution. The following are some major conclusions from a detailed analysis of the steady state and dynamic performance of the FCS shown in Fig. 1.

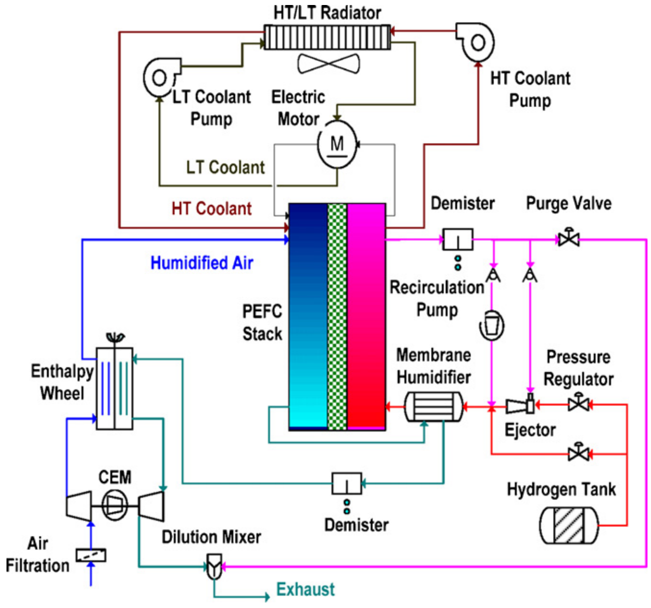

Fig. 1. Argonne 2005 FCS schematic diagram. Argonne 2010 FCS shares the same schematic but with improved materials and appropriately modified operating conditions.

- Meeting the target of 50% system efficiency at rated power requires the stack to operate at 0.7 V cell^{-1} or higher, and results in stack specific power and power density being lower than the targets of 1500 W kg^{-1} and 1500 W L^{-1}.
- The near-term targets for stack specific power, power density and precious-metal loading (1 g Pt kW^{-1}) can be satisfied, but only by relaxing the system efficiency target.
- Durabilities of the Pt electrocatalyst finely dispersed on high-specific area carbon support and of the perfluorosulfonic acid