Environment Protection Engineering

Vol. 32 2006 No. 1

JANUSZ R. JEWULSKI*, ZBIGNIEW S. RAK*

FUEL CELLS – THE OPPORTUNITY FOR ENVIRONMENTAL PROTECTION

Fuel cells combine high-efficiency power generation with near-zero emissions, fuel flexibility, polygeneration capabilities, low noise level and CO_2 emission reduction scheme, either implied by high electric efficiency or explicitly by means of CO_2 sequestration. Application of fuel cells in urban environment, in both transportation and stationary markets, may reduce pollution levels. A wide array of applications is under development, ranging from fuel cell scooters, cars and buses to micro-scale (~ 1–5 kW), small-scale (~100–250 kW) and medium-scale (~1–10 MW) combined heat and power (CHP) systems. Compressed hydrogen is a fuel of choice for PEMFC transportation applications, while multi-fuel approach was demonstrated for SOFC and MCFC applications. The fuel cell market is experiencing 30% annual growth rate driven mostly by small stationary and portable fuel cells. Most of the fuel cell applications are in a commercial demonstration stage and mass production is not expected to start before 2010.

1. INTRODUCTION

The attractiveness of fuel cells as electricity generators is derived from political (energy independence), environmental (air pollution, global warming) and economic (high cost of fuel) aspects. There are currently over 100 fuel cell manufacturers, with activities concentrated in North America, Europe and Japan.

The inefficient electric power generation based on conventional combustion and non-sustainable fuel sources can be overcome by the use of fuel cells that convert electrochemically a chemical energy of the fuel to electricity. The resulting gains in the electrical efficiency may approach 15%–40%. These gains, combined with low emissions, fuel flexibility (SOFC, MCFC), schemes for CO_2 emission reduction or sequestration, and high volumetric power density, make fuel cells a prime facility to replace conventional combustion systems. Nonetheless, only the last decade brought technological advances necessary to commercialize fuel cells. There are several types of fuel cells under development. Among them, polymer electrolyte membrane fuel cells (PEMFC) are suit-

---

* Institute of Power Engineering, ul. Augustówka 5, 02-981 Warszawa, Poland.

able for automotive and small stationary applications. Because of a relatively low operating temperature (60–80 °C), cogeneration potential of PEMFC is somewhat limited. The solid oxide fuel cells (SOFC) and molten carbonate fuel cells (MCFC), operating at the temperatures from 650 °C (MCFC) to 750–900 °C (SOFC), are considered a favourite for wide stationary applications. PAFC are already commercialized but their market penetration is limited by high cost. A new generation of PAFC is developed by UTC Power with the goal of extending their lifetime to 80,000 hr.

The fuel cell systems are based on electrochemical, direct energy conversion, therefore they do not have to obey the Carnot limitation. The overall electrical efficiency (η_{EL}) of the fuel cell system is defined by both power generated by the fuel cells (P_{FC}) and cogeneration electric power (P_{GT}):

$$\eta_{\mathrm{EL}} = \frac{\sum P_{\mathrm{FC}} + \sum P_{\mathrm{GT}}}{\Delta H^{\mathrm{o}}},$$

where ΔH^{o} is a lower heating value of the fuel (LHV).

All fuel cells generate heat in addition to electric power (figure 1). The amount of heat generated in the stack depends on fuel cell performance (figure 2). Since the reaction of the fuel supplied to fuel cell stack is not complete, additional heat can be generated when exhaust fuel is combusted. This additional, high-quality co-generation heat, depending on its application, can be used for supplemental power generation with gas and steam turbines, heating, hot-water generation, cooling or combined use. Additional benefits can be gained when fuel is reformed internally in the fuel cell stack (e.g., SOFC, MCFC), utilizing stack generated heat in the endothermic steam reforming reaction.

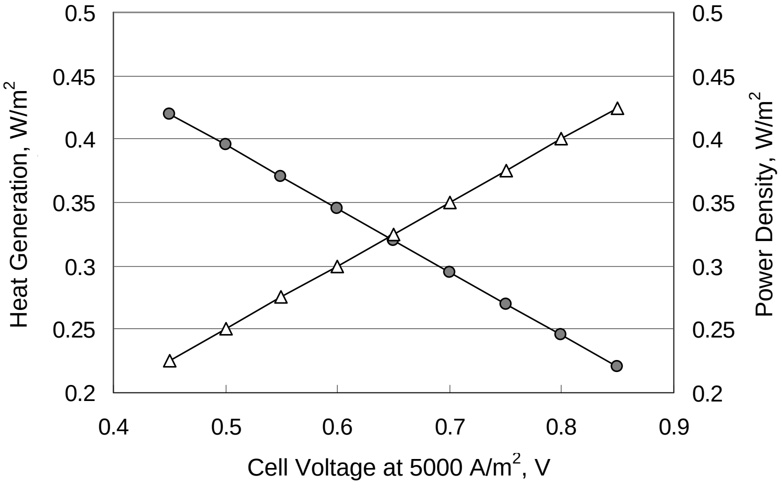

Fig. 1. Heat (triangles) and electric-power generation (circles) in the SOFC cell as a function of cell performance

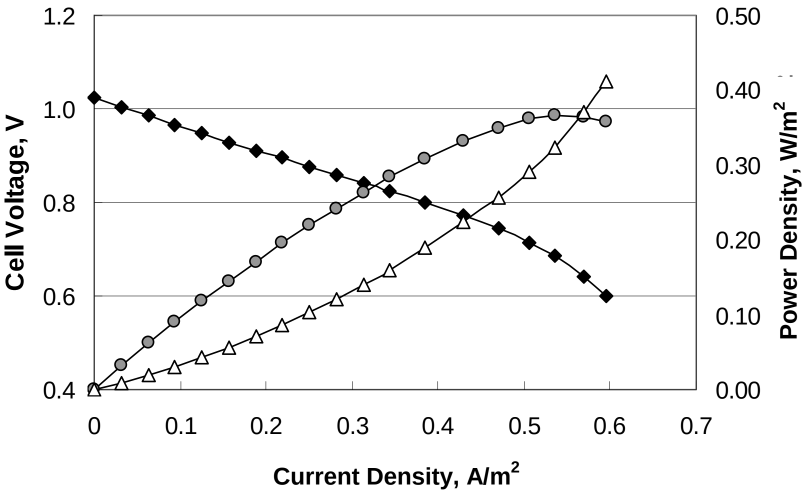

Fig. 2. Typical performance of the SOFC fuel cell manufactured at OC CEREL (diamonds) and the corresponding electric power (circles) and heat generation (triangles)

Decentralized, smaller CHP systems allow efficient energy use close to the energy consumers. However, fuel cells are in market competition with already existing power-generation systems such as reciprocating gas engines, diesel engines, gas and steam turbines as well as solar and wind technologies.

2. FUELING OPTIONS AND SAFETY

A wide range of fuels is suitable for fuel cells operation, originating from mineral based fuels (natural gas, coal, diesel, gasoline), electrolysis (hydrogen) or renewable resources (methanol from wood distillation, ethanol from wheat, rice, sunflower, potatoes, sugar cane and sugar beets or cellulose, wood waste, municipal solid waste and bio-diesel from soybean oil, used oils or fats, landfill gas etc.). The selection of fuel defines overall system efficiency [1].

With the exception of hydrogen, all other fuels have to be subjected to steam reforming or to partial oxidation process. Hydrogen necessary to operate fuel cells can be stored directly or produced on site by steam reforming or partial oxidation process (POX). Among liquid fuels, both methanol and ethanol are, in general, safer than gasoline [2]. Among gaseous fuels, hydrogen as a fuel for fuel cells is safer than natural gas (the table). Physical characteristics of hydrogen, such as high buoyancy and molecular diffusion in air, lead to its fast dispersion. When leaking from a closed container hydrogen will float upward diluting fast in air.

Table

Safety-related characteristics of the selected fuels
(LFL/HFL – lower/higher flammability limit; LEL/HEL – lower/higher explosive limits)

Compound	Flammable/explosive limits, vol. %		Buoyancy (in air)
	Min(LFL, LEL)	Max(HFL, HEL)	
Hydrogen	4.0	75	0.07
Methanol vapour	6.7	36.5	1.1
Ethanol vapour	3.3	19	1.6
Methane	5	15	0.55
Gasoline (unleaded)	1.2	7.1	3.4–4
Propane	2.1	9.5	1.5

3. FUEL CELL COMBINED HEAT AND POWER SYSTEMS (FC-CHP)

The fuel cell-based CHP systems provide electric power together with heat that can optionally be used for heating and cooling purposes [3]. In today's market, the demand for space heating is reduced but power-to-heat ratio is progressively increasing due to relatively higher demand for electricity [4]. This is in-line with the FC-CHP system characteristics. SOFC have a targeted cost of €400–€500 with electrical efficiency ranging from 30% to 55% and theoretically up to 80% in large-scale FC-CHP systems.

In the 1–5 kW micro-CHP range (single family house), PEMFC and SOFC systems offer similar characteristics ($\eta_{\mathrm{EL}} \sim 30\%$, heat-to-power ratio ~ 0.55) and both systems are being pursued [5]. The overall efficiency exceeds 80% with CO_2 release 25–50% lower than in conventional systems. There is a wide range of specific applications pursued, including space heating, hot-water boilers and cooling systems combined with simultaneous electricity generation. The micro-FC–CHP systems are typically fuelled by natural gas, but other options have been tested (e.g., ethanol).

In the 200–1000 kW range (hospitals, office buildings), SOFC-based CHP systems offer some advantages ($\eta_{\mathrm{EL}} \sim 60–70\%$, heat-to-power ratio of ~ 2.5 for combined SOFC and gas turbine system). Although the SOFC technology is still in an early stage of market development, the already demonstrated efficiency of 200 kW SOFC+GT installations (58%) is comparable to electrical efficiency achieved in high-power (100's MW) combined steam and gas turbines installations.

4. FUEL CELLS FOR TRANSPORTATION

As opposite to medium-size stationary applications, automotive fuel-cell market is dominated by PEM fuel cells. The PEMFC have targeted the durability of 5,000 hr at the cost of 50–100 €/kW (2010). Fuel-cell bus (FCB) technology is pursued by several

PEMFC developers (Ballard, UTC, Hydrogenix, Plug Power) in cooperation with bus manufacturers (Mercedes-Benz, Van-Hool, Americas AC Transit). With total stack power ranging from 60 kW to over 200 kW, fuel-cell operation is usually supported by batteries and ultracapacitors (ISE Corp., Maxwell) for regenerative storage of breaking energy. Daimler-Chrysler is currently testing over 30 fuel-cell Mercedes-Benz Citaro buses (FCB) based on 200 kW PEMFC system developed by Ballard. Testing of FCB's in Europe was just extended into 2007 in 7 European cities. Similar efforts are under way in Japan (Toyota – Hino) and Europe (UTC Power – Van Hool). PEM FCB's are fuelled by compressed hydrogen (350–700 bars) with water vapour as the only product of the electrochemical reaction in fuel cell. The hydrogen fuel-cell buses are assumed to generate zero emissions of particulates and NO_x [6]. Since FCB's are still in a testing stage, their price tag is currently close to € 2 million.

Almost all car manufacturers are currently involved in the development of passenger fuel-cell vehicle (FCV). Early this year, Honda unveiled plans to start production of the FCX Concept fuel-cell vehicle in 2009–2010, based on 105 kW PEMFC stacks fuelled by compressed hydrogen. The projected range of over 500 km is similar to that of gasoline-fuelled cars. Honda announced also testing of Home Energy Station, as a home-based refueling alternative based on natural gas reforming. The Home Energy Station, in addition to hydrogen production and storage, is capable of supplying back-up electricity for home in the case of power outage.

Other transportation applications, powered by smaller PEMFC or DMFC stacks, include golf carts, bikes, boats, APU's, wheelchairs, etc.

ACKNOWLEDGEMENTS

The support of the Commission of the European Communities under contract No MTKD-CT-2004-509811 is acknowledged.

REFERENCES

[1] COUTELIERIS F.A., DOUVARTZIDES S., TSIAKARAS P., *The importance of the fuel choice on the efficiency of a solid oxide fuel cell system*, Journal of Power Sources, 2003, 123, 200–205.

[2] PLOTKIN S.E., *Assessment of PNGV Fuels Infrastructure: Infrastructure Concerns Related to the Safety of Alternative Fuels*, Argonne National Laboratory, Report No. ANL/ESD-TM-160, June 2000.

[3] WEBER C., MARECHAL F., FAVRAT D., KRAINES S., *Optimization of an SOFC-based decentralized poly-generation system for providing energy services in an office-building in Tokyo*, Applied Thermal Energy (in press).

[4] BAUEN A., HART D., *Assessment of the environmental benefits of transport and stationary fuel cells*, Journal of Power Sources, 2000, 86, 482–494.

[5] KREWITTA W., NITSCHA J., FISCHEDICKB M., PEHNTC M., TEMMING H., *Market perspectives of stationary fuel cells in a sustainable energy supply system – long-term scenarios for Germany*, Energy Policy, 2006, 34, 793–803.

[6] KARLSTRÖM M., *Local environmental benefits of fuel cell buses – a case study*, Journal of Cleaner Production, 2005, 13, 679–685.

OGNIWA PALIWOWE – SZANSA NA OCHRONĘ ŚRODOWISKA

Ogniwa paliwowe łączą wysoką sprawność wytwarzania prądu z bliską zeru emisją zanieczyszczeń, wielopaliwowością, możliwością współwytwarzania ciepła, niskim poziomem hałasu oraz możliwościami ograniczenia emisji CO_2 zarówno pośrednio dzięki wysokiej sprawności, jak i bezpośrednio w wyniku sekwestracji CO_2. W środowisku miejskim ogniwa paliwowe użyte w celach zarówno transportowych, jak i stacjonarnych mogą przyczynić się do redukcji zanieczyszczeń.

Prace nad ogniwami obejmują wiele ich zastosowań począwszy od samochodów i autobusów o napędzie na ogniwa paliwowe, a skończywszy na systemach współwytwarzania mocy elektrycznej i ciepła w mikroskali (~ 1–5 kW), małej skali (~100–250 kW) oraz średniej skali (~1–10 MW). Sprężony wodór jest preferowany jako paliwo w środkach transportu z ogniwami typu PEM, a wielopaliwowość została zademonstrowana w zastosowaniach z wykorzystaniem ogniw typu SOFC oraz MCFC. Tempo wzrostu rynku ogniw paliwowych osiąga 30% w skali roku, w większości zakresie bardzo małych mocy. Większość zastosowań ogniw paliwowych jest na etapie demonstracji, a ich produkcja seryjna nie jest oczekiwana przed rokiem 2010.