

Prospects of different fuel cell technologies for vehicle applications

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Abstract

Two potential applications of fuel cell power plants in passenger cars: drive and auxiliary power units are presented. Then, specific constraints for fuel cell stack and power plants are evaluated for each application. After the description of the different fuel cell technologies, they are compared mainly at the stack level and power plant level if significant, depending on various criteria corresponding to the different vehicle applications. Finally, technologies of potential interest for use in vehicles are evaluated. Proton exchange membrane fuel cell (PEMFC), providing short starting and response times at the stack level seems the most suitable technology for drive application. In an auxiliary power unit application, the solid oxide fuel cell (SOFC), which allows easier operating with a traditional engine fuel because of simplified fuel processing and presents good performance, may find an application. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Fuel cells; PEMFC; SOFC; Vehicle; Fuel processing; Auxiliary power unit

1. Introduction

Important research and development efforts are deployed by car manufacturers to develop fuel cell vehicles, planned for start of production 2003–2005 by Honda, Ford, Toyota, General Motors, Daimler–Chrysler and Renault/Nissan [1]. The Californian market is considered the leader for fuel cell vehicles today. Actually, from 2003 on, 10% vehicles being sold by manufacturers should meet ZEV requirement. Only pure electric vehicles and hydrogen fuel cell vehicles can presently achieve “Zero Emission Vehicle”. To implement such a rapid transition, the California Fuel Cell Partnership (CAFCP) has been established to demonstrate fuel cell vehicles. The CAFCP units car manufacturers (Daimler–Chrysler, Ford, General Motors, Honda, Hyundai, Nissan, Toyota and Volkswagen), energy companies (BP, Shell, Texaco and Exxonmobil), proton exchange membrane fuel cell (PEMFC) manufacturers (Ballard Power Systems and International Fuel Cells), government partners (including CARB) and associate partners (Air Products and Chemicals Inc., Praxair, Methanex Corporation) [2]. Mostly, all of the car manufacturers, however, plan a subsequent market penetration in 2010.

Until now, fuel cells are planned mainly for the drive application. However, other vehicle applications may be considered for this power source such as auxiliary power units. A fuel cell technology attracting most of the investment is the PEMFC. Though this technology achieves, today, power densities compatible with drive applications, it shows nevertheless, some drawbacks. For a fuel other than hydrogen, the sensitivity of the PEMFC to CO requires the installation of at least two reformat purification stages, which results in increasing the volume and complexity of the fuel supply system. California State has, therefore, chosen hydrogen and not methanol, on board of a fuel cell vehicle [3]. Besides, though the PEMFC operating temperature is compatible with short start and response times, a higher temperature (above 120–130 °C) would make the evacuation of generated heat easier. Nevertheless, the cost of a PEMFC drive train is still expensive as compared with the cost of a traditional engine. Lately, a direct methanol fuel cell (DMFC)-based drive train has been demonstrated in a prototype by Daimler–Chrysler [4] and solid oxide fuel cell (SOFC) as a power unit by BMW.

Among other fuel cell technologies such as, for example, the DMFC or the SOFC, would some of them have more potential than the PEMFC? For which vehicle application? What type of fuel cell technology will be used in a vehicle beyond 2010?

This article is intended to give some answers to these questions by comparing the different fuel cell technologies,

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mainly concerning their stack characteristics. This study has been carried out by a bibliographic study focussed on different fuel cell technologies. Initially, the constraints resulting from different vehicle applications for the fuel cell power plant and stack itself will be discussed. These constraints will be evaluated for different fuel cell technologies. In conclusion, we will try to assess a potential of each technology for vehicle application.

2. Fuel cell stack, system and power plant

A distinction is made between single cell, fuel cell stack, fuel cell system, without the fuel processing steps and fuel cell power plant with the fuel processing steps. The stack is an assembly of elementary, or single cells (assembled anode, electrolyte and cathode), interconnected by bipolar plates (also called interconnects) in a planar technology configuration. An example of a scheme of a repeating unit in a planar PEMFC stack is given in Fig. 1. The system without fuel processing steps is a fuel cell stack together with all auxiliaries (or balance of plant (BoP)) attached to the stack, except the fuel processing or supply. The fuel cell system comprises the oxygen supply and possibly the water loop, which allows the recovery of the generated water, to manage the water necessary for the fuel processing or reformer operation and to moisten the fuel cell and/or gases. The fuel cell system with reformer (or fuel processor) called subsequently a fuel cell power plant comprises the fuel cell system without reformer and the fuel supply system, that

includes the fuel processing (or reforming) step(s). A schematic layout of a complete fuel cell drive train with the fuel cell power plant and the fuel cell system is shown in Fig. 2. The fuel cell stack can be fuelled, on the anode side, by methanol, methane (direct or reformed, depending on the technology) or reformed hydrocarbons (like, for example gasoline and diesel) and on the cathode side, by oxygen from air as an oxidizer. The fuel supply circuit comprises fuel processing reactors which convert the fuel in a hydrogen-rich gas and purifies it to the level needed for the fuel cell stack to operate efficiently. The oxidizer circuit comprises essentially a fan for the stack operating at ambient pressure or a motor-driven compressor, which increases the air pressure for a stack operating under pressure.

Within the scope of this study, different fuel cell technologies will be primarily evaluated at the single cell and stack level, but sometimes also at power plant level if it is considered as important for the evaluation for vehicle application.

3. Fuel cells: vehicle applications

The fuel cell, source of electric energy for a vehicle, can be considered for two types of applications: drive or auxiliary power source.

3.1. Drive application

Fuel cell drive trains are developed to replace conventional internal combustion engines. The aim is to produce lower pollutant emissions, reduce fuel consumption, together with allowing a long range (for example 600 km), contrary to electric vehicles with batteries. These vehicles have, indeed, a limited range of 150–250 km maximum even with advanced batteries, such as nickel metal hydride and lithium-ion batteries [5].

Two main different fuel cell drive trains can be considered: a fuel cell drive train with a fuel cell power plant of high power and a fuel cell drive train with a fuel cell of low power associated with a battery that ensures the driving power (e.g. the fuel cell is used as a range extender). Fuel cell power plants of high power ensure the driving power with or without a back-up battery to help for start-up, transient or high power demand, for example, during acceleration.

Prospects for low emissions, low fuel consumption and high range depend strongly on the fuel cell power plant fuel. Only hydrogen allows the vehicle to be a zero emissions vehicle locally, however, globally from well-to-wheel, carbon dioxide and pollutants can be produced, depending on the selected energy source to produce hydrogen. Moreover, current hydrogen storage devices are still expensive and bulky, and its wide use implies the development of a hydrogen-dedicated infrastructure. Besides, compressed hydrogen storage volumes do not presently allow to reach sufficient vehicle ranges. The hydrogen refueling time is also not quick enough for vehicle customers. Accordingly, hydrogen fuel

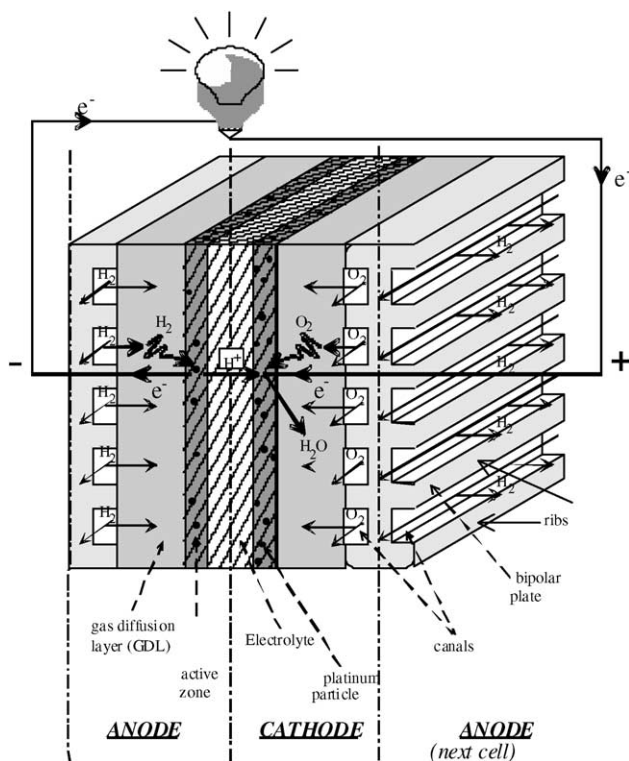


Fig. 1. Scheme of a repeating unit in a PEMFC stack.

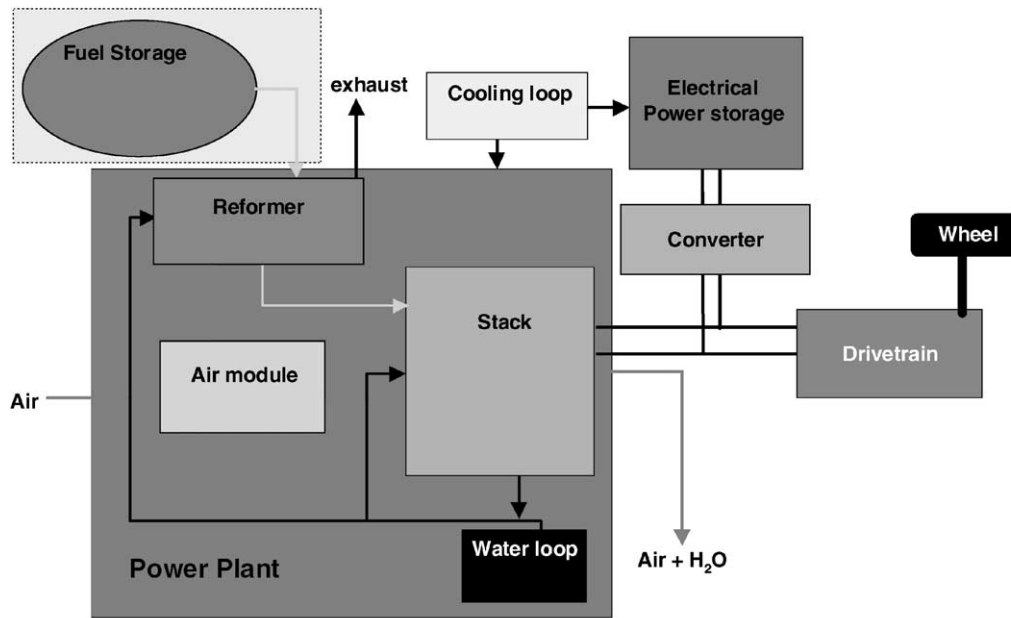


Fig. 2. Simple scheme of a gasoline or methanol/air complete fuel cell drive train with the fuel cell power plant.

cell vehicles problematic is very close to the one of pure electric vehicles.

Other considered fuels, such as gasoline, diesel and methanol will always produce carbon dioxide, and the fuel processing steps decrease the total efficiency of the power plant. Therefore, the choice of the power plant fuel results from an emissions/volume/cost compromise (including construction changes).

3.2. Auxiliary power source

The present trend is to increase the electrical requirement of the vehicle auxiliaries, for comfort, reduction of consumption and emissions and safety devices. This electrical energy is actually delivered both by the auxiliary battery and the engine through an alternator. The standard voltage of the on-board electrical network is to be changed from 12 to 42 V, with battery dimension, cost increased and an energy management complicated to optimize their functioning. Moreover, the alternator low efficiency stimulates an interest for other less energy-consuming generation systems.

A fuel cell power plant can be used as an auxiliary source of power or APU capable of supplying the power to vehicle auxiliary devices. That would allow the required battery power to be reduced, as well as, in the long term, to suppress the alternator. The fuel cell power plant should also use the same fuel as the conventional engine.

3.3. Power of the plant, stacks and operating mode depending on the application

The power ranges of fuel cell power plants are indicated depending on application in Table 1.

The fuel cell power plant and stack operating mode depend on the application. Concerning the drive application, the consumer will require the vehicle to start-up quickly, and a target value is, for example that the vehicle starts in less than 5 s. The drive train also has to follow the dynamics in different operating conditions (e.g. town, highway, and mountain, etc.) and quick response times are needed. When the fuel cell power plant is used as the main source for driving the vehicle, quick starting and response times will be needed for all its components (e.g. different fuel processing steps, stack, air compressor or fan). A back-up battery can be used to make-up for a very quick start-up and response time. To optimize its capacity and size the battery should not be used alone for a long time, for example not for more than several minutes. When the battery provides mainly the power, the fuel cell power plant will not need so stringent starting and response time targets and it can also be operated almost in a continuous mode. For auxiliary power unit application, a fast power plant start-up time will be needed for operation when the engine is off. Fast power plant response times are also needed to provide for the quick variation of the vehicle auxiliaries power electronics, or a back-up battery should be used.

Table 1

Indicative fuel cell system and power plant power as a function of specific vehicle applications

Application	System power (kW)
Drive with a fuel cell of high power	70–80
Drive with a fuel cell of low power	10–20
Auxiliary power unit	5–10

4. Constraints for fuel cell power plants and stacks in a vehicle

4.1. Vehicle application constraints on the power plant

The main fuel cell power plant constraints for vehicle applications are listed in Table 2, first column. The fuel cell drive train and power plant weight and volume should allow it to be integrated into the vehicle. Mass and volume power density targets for drive application with a fuel cell of high power are, for example for 2010 for the stack around 1 kW kg^{-1} and 1 kW l^{-1} [6]. The environmental cleanness gain and efficiency should not significantly increase the vehicle cost. A fuel cell drive train target for a high power plant for drive application for 2010 is, for example 3300 €, that is for a 60 kW power plant 55 €/kW [6]. If a fuel, other than gasoline is chosen, like diesel or LPG, it is necessary to consider infrastructure changes in fuel production, distribution, as well as storage systems. For this reason, the power plant fuel is a serious criterion for vehicle applications. The power plant efficiency is linked to the fuel consumption and emissions, and in particular, carbon dioxide (CO_2). Thus, its efficiency allows us to assess the environmental benefit in terms of CO_2 emissions and energy saving resulting from fuel cell power plant integration whatever its intended application. An example of the efficiency target in 2010 for the power plant, on a cycle, for drive is 45% [6]. The environmental aspect of a fuel cell vehicle is also evaluated on the basis of emissions of pollutants, which should meet the EURO 2000 targets divided by 100 in the year 2010 [6]. For carbon dioxide, a well-to-wheel 2010 target for drive application is 100 g km^{-1} on cycle [6]. The power plant life cycle should attain for drive application a traditional engine life, i.e. 5000 h on operation. Depending on the intended application and required cell power, the target values of starting and response times shall be increasingly restrictive. For drive application with a fuel cell of high power, a power plant starting time of less than 5 min. and a stack response time inferior to 1 ms should be reached [6]. Finally, power

plant safety and reliability should be taken into consideration from the very beginning of the design stage.

4.2. Single cell and stack-related constraints

The power plant constraints resulting from vehicle application are tabulated for the single cell and stack level and possibly power plant, if significant, in Table 2, second column.

5. Different fuel cell technologies

Table 3 presents the different fuel cell technologies, their principal characteristics, intended applications, worldwide developers and their advanced development achieved.

Most often, fuel cells are classified according to the electrolyte used that settles the operating temperature. However, another classification of fuel cells may be set up according to the fuel and the fuel supply used, either direct or indirect. Table 3 displays the usual classification system, except for the DMFC that we wished to separate from the PEMFC because of its direct methanol supply. Low temperature cells (up to $200 \text{ }^\circ\text{C}$) operate with hydrogen or possibly methanol, while high temperature fuel cells (molten carbonate fuel cell, MCFC and SOFC) allow hydrogen and carbon monoxide to be oxidized.

Table 4 shows the electrolyte, electrode and bipolar plate materials currently used for the different fuel cell technologies. While low temperature fuel cells need noble platinum or platinum-based alloys as catalysts for hydrogen oxidation and oxygen reduction (there are, nevertheless, some prospects for alkaline fuel cell (AFC) for non-noble metal catalysts), non-noble catalysts are used in high temperature fuel cells. High platinum and platinum-ruthenium loading are needed for DMFC to optimize its performances: on the anode side, to enhance the oxidation of methanol and on the cathode side to prevent poisoning from methanol crossover through the electrolyte. Phosphoric acid fuel cell (PAFC) and PEMFC platinum loading have been greatly reduced in

Table 2

Main fuel cell power plant constraints for vehicle application and corresponding stack constraints

Power plant constraints	Corresponding single cell and stack constraints (possibly power plant if significant)
Mass, volume	Single cell and stack power density, stack operating pressure, fuel cell power plant power density
System efficiency	Stack and fuel cell power plant efficiency
Cost	Fuel cell stack raw material and process cost, corresponding system cost, potential stack fuels
Kind of fuel	Acceptable stack contaminant percentage and associated single cell or stack performance decrease and reversibility, associated fuel processing constraints
Emissions	Pollutants at the fuel cell stack outlet
Lifetime and maintenance operations	Fuel cell stack lifetime and maintenance operations, fuel cell stack operating temperature
Starting and response time	Stack, system and power plant thermal management, stack problems associated with start, stop, sudden power change, stack performances degradation
Safety and reliability	Stack stop of operation, electrolyte loss, mixing of $\text{H}_2\text{-O}_2$, etc.

Table 3
Different fuel cell technologies, main characteristics, intended applications and main developers

Name	Symbol	Operating temperature (°C)	Electrolyte	Type of electrolyte	Oxidized compounds	Water generated on	Intended applications	Development advance	Principal developers/companies
Proton exchange membrane fuel cell	PEMFC	60–90	Proton exchange membrane (e.g. Nafion [®])	<i>Solid</i> : polymer which has to be moistened	Hydrogen or methanol (see DMFC)	Cathode side	Vehicle (drive), stationary ^a (housing, cogeneration), portable	Prototypes of vehicles, demonstration of housing systems and 200 kW systems	Ballard (Canada), Nuvera (Italy/US), IFC (USA), H Power (USA), Plug Power (USA), Avista (USA), Energy Partners (USA)
Alkaline fuel cell	AFC	60–100	Potash KOH generally in aqueous solution at 35% in weight	<i>Liquid</i> : circulating or in a matrix	Hydrogen	Anode side	Vehicle (hybrid), spatial	Development: London taxis and small vehicles used for 30 years by NASA in space flights	IFC/UTC (USA), Zetek (GB), Astris Energy (Canada)
Direct methanol fuel cell	DMFC	60–120	Proton exchange membrane (e.g. Nafion [®])	<i>Solid</i> : polymer which has to be moistened	Methanol dissolved in water liquid or steam	Cathode side	Vehicle (hybrid) portable	Prototypes of 5 kW systems and small vehicles, telephones and computers	Ballard (Canada), Daimler-Chrysler, Motorola (USA), with US laboratories, laboratory partnership in Japan including Nissan
Phosphoric acid fuel cell	PAFC	160–200	Pure phosphoric acid	<i>Liquid</i> : in a porous matrix of silicium carbide	Hydrogen	Cathode side	Stationary ^a (cogeneration)	Marketing of cogeneration systems 200 kW (ca. 200 worldwide)	ONSI (joint venture IFC–Fuji–Toshiba, USA–Japan), Fuji (Japan), Toshiba (Japan)
Molten carbonate fuel cell	MCFC	600–700	Old generation Li ₂ CO ₃ /K ₂ CO ₃ , new generation Li ₂ CO ₃ /Na ₂ CO ₃	<i>Liquid</i> : in porous matrix of lithium aluminate	Hydrogen and CO	Anode side	Stationary ^a (cogeneration, power plants)	Demonstrations of power stations 250 kW to 2 MW	FCE (USA), MTU (Germany), IHI (Japan), Hitachi (Japan), Ansaldo (Italy)
Solid oxide fuel cell	SOFC	700–1000	Yttrium oxide-doped zirconia YSZ: (ZrO ₂) _{1-x} (Y ₂ O ₃) _x , currently x = 3 or 8	<i>Solid</i> (ceramic)	Hydrogen and CO	Anode side	Vehicle (APU) stationary ^a (housing, cogeneration)	Exhibitions of housing 1 kW and cogeneration systems 200 kW	Siemens–Westinghouse (Germany–USA), Global Thermolectric (Canada), Sulzer Hexis (Switzerland), Mitsubishi (Japan)

^a Among stationary applications, three ranges are considered: housing power systems 1–10 kW (electric supply for a house); cogeneration, production of electric energy and heat, power systems of 50–1000 kW (stores, flats, buildings); remote power stations, power systems 5–20 MW.

Table 4
Current constitutive materials of the different fuel cell technologies

Technology	Electrolyte	Anode	Cathode	Bipolar plates
PEMFC	Nafion [®] membrane	Carbon cloth, carbon particles with high specific area, platinum particles, weight 0.1 mg cm^{-2} , PTFE, Nafion [®]	Carbon cloth, carbon particles with high specific area, platinum particles, weight 0.3 mg cm^{-2} , PTFE, Nafion [®]	Machined carbon or stainless steel
DMFC	Nafion [®] membrane	Carbon cloth, carbon particles with high specific area, platinum–ruthenium particles, weight 2 mg cm^{-2} , PTFE, Nafion [®]	Carbon cloth, carbon particles with high specific area, platinum particles, weight 2 mg cm^{-2} , PTFE, Nafion [®]	Machined carbon or stainless steel
AFC	Solution of KOH at 35–40 wt.% circulating or in a matrix	Hydrophobic layer (PTFE), carbon catalyst (platinum particles with 0.3 mg cm^{-2} loading or cobalt-based catalyst) [7]	Hydrophobic layer (PTFE), carbon catalyst (platinum particles with 0.3 mg cm^{-2} loading or cobalt-based catalyst) [7]	Current collection by nickel mesh and distribution of gases, water and electrolyte with plastic frame [7]
PAFC	Phosphoric acid in a porous matrix	Carbon cloth as a support, catalyst layer: PTFE + carbon black with high specific area + platinum particles at 0.1 mg cm^{-2}	Carbon cloth as a support, catalyst layer: PTFE + carbon black with high specific area + platinum particles at 0.5 mg cm^{-2}	Graphite
MCFC	Carbonates (lithium–sodium or lithium–potassium) in a porous matrix of lithium aluminate	Nickel–chromium alloy with 10 wt.% chromium	Porous nickel oxide	Stainless steel with protective layers at the anode and cathode sides
SOFC	Yttria-doped zirconia (YSZ), thickness 10–500 μm	Ni/YSZ cermet of 30% porosity	Strontium-doped lanthanum manganite of 30% porosity	LaCrO ₃ or FeCr alloy or stainless steel depending on the operating temperature

the last 10 years. On the cathode side, the platinum loading is usually higher to enhance the oxygen reduction reaction.

PEMFC (DMFC) and SOFC have a solid electrolyte, although the current PEMFC membrane (electrolyte) has to be humidified to reach sufficient conductivity. The other technologies use a liquid electrolyte, either circulating or in a porous matrix. The fuel cells with liquid electrolytes were the first fuel cells developed. The discovery of the solid electrolytes has allowed advances particularly in the management of stops and starts. Performances have also progressed, as the electrolyte thickness can substantially be decreased with solid electrolytes.

Research on low cost and higher working temperature membranes are carried out for PEMFC (DMFC) to replace the Nafion[®]. SOFC are all ceramic devices and these materials are known to be brittle. Constitutive material cost considerations will be discussed later.

6. Evaluation of single cell and stack parameters for the different fuel cell types

In this section, the different stack criteria for vehicle application, as shown in Table 2, will be evaluated for the different fuel cell technologies presented in Table 3.

6.1. Single cell and stack power density/stack operating pressure

6.1.1. Single cell and stack power density

6.1.1.1. *Single cell level.* In Fig. 3, updated single cell performances obtained by several fuel cell developers are

compared. We have chosen to present performances achieved in operation with air as the oxidant (added of CO₂ for MCFC) and possibly hydrogen (except for DMFC, PAFC and MCFC) at atmospheric pressure or usual operating pressure for the DMFC. This data is only qualitative and allows us to see a first comparative outlook on performance prospects for each type of fuel cell technology.

The planar SOFC single cell with a thin electrolyte layer, developed by Global Thermoelectric, presents the highest voltage performance even at 700 °C. The curve slope at 700 °C is, however, steep due to the medium conductivity range of the electrolyte and the lower cathode activity at this temperature.

The PEMFC technology shows slightly lower voltages than planar SOFC at lower current densities. The PEMFC Ohmic resistance is, however, lower and allows higher voltages than SOFC at 700 °C and at high current density.

The Siemens–Westinghouse SOFC (tubular technology) yields performances lower than the planar technology.

The MCFC and the PAFC are ranked just below. However, the results of IHI (MCFC) are falling in the low power density range (less than 120 mA cm⁻²) and the PAFC of Mitsubishi operate within a limited range of voltage and current (0.6–0.7 V and 150–300 mA cm⁻²). These limited ranges are probably chosen in order to avoid electrode corrosion and to extend the lifetime.

The AFC cell performance is much too low in air at ambient pressure (Zetek). Zetek performances are indeed fairly medium: the power density is limited to below 150 mA cm⁻² and the current–voltage curve slope is very steep. The good performances obtained with pure oxygen and at high pressures, e.g. 14 bar (application in space projects) are indeed not found under more practical conditions.

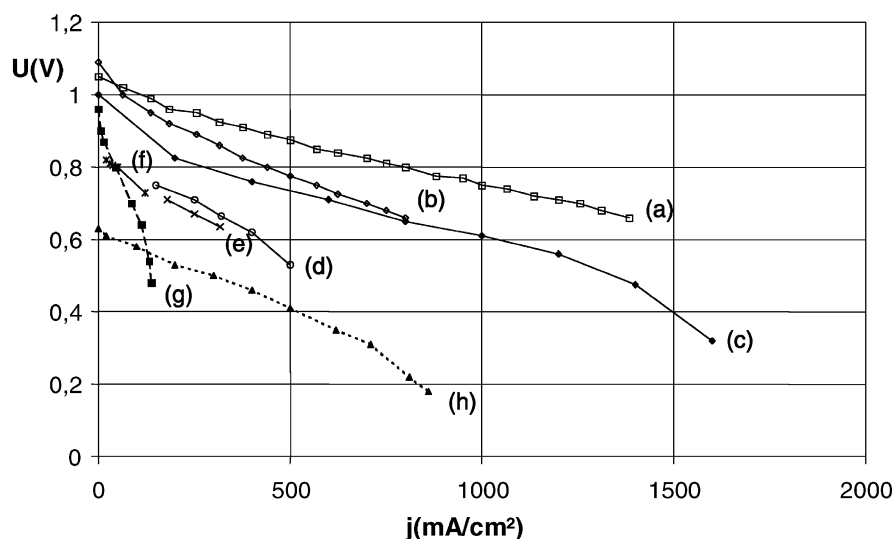


Fig. 3. Comparative performances of different fuel cell technologies on air at the cell level: (a) planar SOFC, Global Thermoelectric, H₂ 1 bar, 900 °C [8]; (b) planar SOFC, Global Thermoelectric, H₂ 1 bar, 700 °C [8]; (c) PEMFC, Gore, H₂ 1 bar, 60 °C [9]; (d) tubular SOFC, Siemens–Westinghouse, H₂ 1 bar, 1000 °C [10]; (e) PAFC, reformat, air, 1 bar, about 200 °C [17]; (f) MCFC, LNG reformat, humidified air + CO₂, 1 bar, IHI [11]; (g) AFC, Zetek, H₂ 1 bar, 70 °C [7]; (h) DMFC, LANL, 110 °C, methanol 1.8 bar/air 3 bar [12].

The DMFC features the lowest voltage at the same power density, though the results presented by Gottesfeld et al. [12] extend to an interesting current density range. This voltage drop is mainly due to the lowest activity of the anode towards the reduction of methanol, to the methanol crossover phenomenon and subsequent drop of cathode performance.

Whatever the type of cell, the single cell performance varies depending on pressure, temperature, fuel and oxidant gas composition and utilization or stoichiometry ratio. Moreover, the performances may be extremely diminished by impurities present in the fuel or oxygen carrier (see Section 6.3). For low temperature fuel cells that require noble metal catalysts for efficient operation, the catalyst load has also a significant impact on single cell performance. This noble metal load should be reduced to a minimum in order to decrease the stack cost.

6.1.1.2. Stack level. As far as the stack is concerned, the PEMFC yields the best performances. The changeover from single cell to stack allows small cell performance losses in a PEMFC stack. Concerning SOFC, thermal management problems may cause high differences between stack and single cell performances. For example, Minh et al. [13] present performances divided by four from single cell to a 26-cell stack. However, other developers show comparable performances at single cell and five-cell stack levels [14]. Progress has to be realized to scale-up stacks together and also keep the single cell performance. In the DMFC, AFC, MCFC and PAFC, the same trends in stack and single cell performance can be found.

6.1.2. Actual power plant volume and mass power densities

Power plant volume and mass power densities depend strongly on the stack and the fuel processing (if needed) performances and the operating conditions (pressure, temperature, fuel, moistening, and stack pollutants tolerance, etc.). For vehicle comparison, the cooling loop and the fuel storage volume and mass must also be considered. Such values are very difficult to find. Some examples are, nevertheless, given below, but they are only qualitative.

Presently, the best power plant power densities are obtained with PEMFC with hydrogen. If the hydrogen power plant, the cooling loop and the fuel storage are considered, projected Renault values for 2010 (based on actual values) give around 250 W kg^{-1} both for compressed and liquid hydrogen [15]. It has, however, to be noted that the storage volume is limited to around 150 l, to allow for vehicle integration. In this case, compressed hydrogen storage allows for a limited range (200–300 km on NMVEG cycle), whereas, liquid hydrogen allows for about 600 km range. Such good power density values are mainly due to the stack high power density. For example, the PEMFC stack Ballard Mark 900 (exhibited in March 2000) presents very compact design features: 1310 W l^{-1} under pressure [16]. For a power plant fed with methanol or gasoline, the power plant,

added to cooling loop and fuel storage added power densities are projected at around $165\text{--}200 \text{ W kg}^{-1}$ [15]. These lower values are mainly due to the fuel processing weight and volume, which does not fully compensate for the gain in storage weight and volume.

AFC presents very low power plant mass and volume power densities: with pure hydrogen, 3 W l^{-1} and 275 W kg^{-1} have been reported [17]. The compact design features have certainly also to be improved at the AFC stack level, increasing the performances of the single cell and stack, limiting Ohmic losses and decreasing the thickness of unit cells in the assembly.

Actual DMFC power plant power densities have not been presented yet. Moore et al. [18] proposes, as a target, a stack volume density of at least 350 W l^{-1} . It can be predicted that power plant power density values would not be sufficient for vehicle integration, if a DMFC stack with Moore et al. features, methanol recirculation, CO_2 separation and air compressor are included.

The volume and mass densities of the PAFC PC25C 200 kW of ONSI are very low at the power plant level with a natural gas reformer: 4 W l^{-1} and 11 W kg^{-1} [7]. Even if the mass and volume constraints in the stationary applications are less stringent than in automobiles, the low performance at the single cell level probably do not allow the PAFC to be integrated into a vehicle.

MCFC power density values of about 8 W l^{-1} and 17 W kg^{-1} (without the fuel purification and inverter) are obtained for the MCFC hot module power plant (developed by MTU) with natural gas [19]. The volume of the CO_2 recycling system from anode to cathode is difficult to reduce, which makes it not compact enough, especially for powers with values lower than 250 kW.

As for MCFC, SOFC accept CO as a fuel. Therefore, gains are expected on the fuel processor power density for SOFC systems operating with other fuels than pure hydrogen. Moreover, a direct supply with natural gas would allow the volume and mass of the power plant to be diminished by eliminating totally or partially the fuel processing stage. Nevertheless, stack and fuel processor insulation is needed for the power plant, which adds to the power plant volume and mass. Even if actual planar SOFC power plant power densities have not been reported yet, good values should be obtained, if single cell performances are transferred to several kW stacks.

6.1.3. Stack operating pressure

Fuel cell performances are enhanced with the increase in the operating pressure whatever the fuel cell technology. For PEMFC stacks, an operating pressure exceeding atmospheric pressure (1.5 or 2–3 bar) is often used in order to obtain high power densities. Probably, mainly for power plant simplicity, the other fuel cell technologies operate at atmospheric pressure, except the DMFC, in which anode/cathode pressure difference allows to limit the methanol crossover and to improve the performances. SOFC are also

operated under pressure (under 10 bar) in hybrid power plants for stationary applications, where the SOFC stack is combined with a gas turbine to improve the global power plant efficiency.

At the power plant level, the pressure value has to be optimized resulting from a compromise between the stack efficiency, the consumption of the power plant's BoP and the power plant water balance. Operation under pressure involves higher consumption of the auxiliary devices compared to operation under atmospheric pressure. A compressor that uses more electric energy also replaces the fan. The pressure has also an impact on the amount of water that can be recycled from the stack. It limits the power plant pressure to a certain value depending on the power plant water needs (fuel processing steps, gases moistening and possibly cooling).

6.2. Fuel cell stack and power plant efficiencies

6.2.1. Stack level

We define the stack efficiency without taking into account fuel utilization or stoichiometry, which is included in the system efficiency as following:

$$\eta = \frac{V_c I N}{\sum_i Q_i \text{LHV}_i} \quad (1)$$

where V_c is the single cell voltage (V); I the stack current (A); N the number of single cells in the stack, i the electroactive species, Q the consumed molar flow (mol^{-1}), and LHV is the low heating value (J mol^{-1}). It is considered that the species are produced in vaporized form.

For high temperature fuel cell (MCFC and SOFC), hydrogen and carbon monoxide are the electroactive species. For direct methanol fuel cell, methanol is the electroactive species. In the case of low temperature fuel cell, hydrogen is the only electroactive species.

If only one electroactive species is used (hydrogen or methanol), the stack efficiency is directly linked to the single cell voltage, as following:

$$\eta_{\text{stack}} = \frac{V_c}{V_{\text{ref}}} \quad (2)$$

where V_{ref} is the reference voltage, function of the species.

In the case of hydrogen:

$$V_{\text{ref}} = 1.25 \text{ V}$$

For DMFC (methanol):

$$V_{\text{ref}} = 1.08 \text{ V}$$

The nominal cell voltage directly depends on the stack volume or stack specific power density (expressed in kW l^{-1}), that is as seen in Section 4, a very important criterion for vehicle application. At constant power density, if we assume close values for cell thickness for the different fuel cells technologies, the different technologies efficiencies can be ranked in the same classification order as the

single cell polarization curves (cf. Section 6.1). This is why SOFC efficiency appears to be very promising. The DMFC efficiency, however, is very low because of poor performances and lower reference voltage compared to hydrogen fuel cells.

For a high temperature fuel cell feed with hydrogen, carbon monoxide and/or methane, simple calculation of stack efficiency cannot be carried out as for pure hydrogen. SOFC single cell simulation, ground on a model developed in hours, at 950°C and 0.7 V gives efficiency (based on the definition above) of 56% with pure hydrogen and 54% with simulated methane reformat (with 58% of H_2 , 15% of CO , 3% of CO_2 and 24% of H_2O [20]). Thus, single cell efficiency seems to decrease slightly from hydrogen towards hydrogen and carbon monoxide feeding.

6.2.2. Power plant level

The efficiencies of the different fuel cell technologies can only be compared at the power plant level for a given voltage. The fuel over stoichiometry (or utilization) and the different power plant auxiliaries, including the fuel processing, reduce the power plant efficiency towards the stack efficiency.

Examples of efficiencies obtained in prototype power plants, as well as a brief description of corresponding power plants, are presented in Table 5. The selected single cell voltage is the rated voltage of 0.7 V , except for the DMFC technology in which such voltages cannot presently be achieved and the PEMFC where projected results on European NMVEG cycle are presented.

Besides the DMFC, for which the power plant efficiency is actually estimated to be 30%, specimens of power plants in fuel cell technology achieve an efficiency exceeding 40–45%. Only the fuel seems to have a determining impact on the values of the power plant efficiency. In fact, for the PEMFC a drop from 55 to 41% on NMVEG cycle is projected due to shifting from pure hydrogen to gasoline. The efficiency criterion seems to deny the possibility of giving preference of one (except for the DMFC) rather than to the other technology, however, it allows to evaluate the low efficiency of the DMFC.

6.3. Fuel cell power plant cost

Estimated stack costs are difficult to find, but some authors have published fuel cell power plant data depending on the fuel cell technology. It should be noted that for technologies still not commercialized, that is all technologies with exception of the PAFC 200 kW power plant developed by ONSI, the disclosed data cannot be considered as entirely reliable.

The cost data of all technologies are presently 100 times higher than the Renault target cost value for drive application (see Section 4.1). Frost and Sullivan [23] and Hart and Bauen [24] have estimated that PEMFC, MCFC and SOFC technologies for large scale stationary application have

Table 5

Examples of fuel cell power plant electrical efficiencies for the different technologies for a cell potential of 0.7 V (0.4 V for DMFC) and on European NMVEG cycle for the PEMFC

Technology	Power plant components/characteristics	Remarks	Power plant efficiency
PEMFC	Hydrogen fuel	Simulation results on NMVEG cycle/2010 projections	55% [15]
PEMFC	Methanol reformat fuel	Simulation results on NMVEG cycle (with simplified fuel processor model)/2010 projections	43% [15], e.g. 80 g CO ₂ for 100 km
PEMFC	Gasoline reformat fuel	Simulation results on NMVEG cycle (with simplified fuel processor model)/2010 projections	41% [15], e.g. 100 g CO ₂ for 100 km
DMFC	PEMFC fed with a methanol solution, with air under a pressure of 2 bar	Assumptions: cell potential of 0.4 V/compressor + auxiliaries losses of 10%	30%
AFC	Hydrogen/air system under atmospheric pressure	Experimental data at nominal power	48% [7]
PAFC	PAFC at atmospheric pressure + gas natural fuel processing	Assumption: dc/ac converter with an efficiency of 80%	50% without dc/ac [16,21]
MCFC	Gas natural internal fuel processing	Measurement done during field trial 1998	47% [22]
SOFC	Without gas turbine	Measurement during field trial	45% [10]
SOFC	Coupled with a gas turbine	Forecast	57% [10]

presently similar costs, in spite of Frost and Sullivan announcing the cost doubled as compared with Hart and Bauen [24]. Kalhammer et al. [25] consider that the DMFC stack cost is 10 times higher than the PEMFC stack cost. High catalyst loads are indeed used in DMFC and performances are lower than those of the PEMFC with hydrogen but also reformat. Concerning DMFC power plant, the high cost of the stack may not compensate for the fuel processor absence enough to allow to obtain a power plant cost comparable to the PEMFC. Operating pressures above ambient are indeed used in DMFC and moreover, the PEMFC stack cost represents the biggest share of the power plant cost.

In terms of forecasts, the PEMFC and the SOFC, according to Frost and Sullivan [23] and Kalhammer et al. [25], would reach the power plant costs within a range of US\$ 1000/kW or US\$ 750/kW. This is still 20 times higher than the drive application target value. However, one should note that the forecasts for the PEMFC for drive application [25] are lower (about three-fold less) than for the stationary application [23]. The different targets of these two applications can explain this difference, namely in terms of lifetime and durability.

The fuel cell stack and power plant cost criteria for vehicle application seems to be the most difficult to meet whatever the fuel cell technology. In the opinion of Kalhammer et al. [25], the DMFC seems to be the technology for which these criteria will be most difficult to meet, as far as it presents a stack cost significantly higher than the PEMFC technology. Other technologies seem to have quite similar updated costs and PEMFC and SOFC power plants are reported to have similar prospects for cost reduction.

6.4. Potential stack fuels and oxidants

A fuel cell produces electricity through two combined reactions: oxygen molecules are reduced at the cathode side and hydrogen molecules are oxidized at the anode side. In high temperature fuel cells, carbon monoxide molecules

can also be oxidized at the anode side. How can these molecules be transferred to the fuel cell? A simple way could be to embark bottles of oxygen and hydrogen, a solution that has been chosen for submarines and space applications. Vehicles are produced in large volumes and the economic criteria are crucial. Therefore, other anodic and cathodic feeding should be provided (Table 6).

6.4.1. Cathodic feeding

The most simple oxygen carrier is the air supply, which contains approximately 20% oxygen and approximately 80% nitrogen. Due to diluted oxygen, the fuel cell (whatever the technology) current density range is, however, lowered compared to pure oxygen operation. A humidifying system can be included if humidified air is needed. Depending on the operating pressure, a compressor or a blower is needed in the air inlet line. Sometimes air has to be heated next to the fuel cell operating temperature (for example to feed SOFC). A heat exchanger is, in this case, added to the air inlet line. Fuel cell performances can also be strongly affected through particles and molecules present in ambient air. Therefore, an air filter should be included in the cathodic inlet line. MCFC and AFC technologies present other features for cathodic feeding. Indeed, the air must be previously purified in CO₂, in the case of AFC, and supplemented with CO₂ coming from the recycling of the CO₂ generated on the anode, in the case of MCFC. Ambient air contains 300–400 ppm of CO₂, whereas, AFC accepts 10–50 ppm of CO₂, depending on the technology. In the case of MCFC, the presence of carbon dioxide is necessary in order to reduce oxygen.

6.4.2. Anodic feeding

Hydrogen is considered as the future fuel (after 2010) and more traditional fuels like gasoline (methanol?) as the near term fuel for fuel cell vehicle application [26]. Systems are also developed with other fuels like diesel, natural gas and liquid gas. Hydrogen storage is indeed still expensive and bulky and involves important changes in the distribution infrastructure.

Table 6
Current fuel and oxidant feeding, corresponding reduced and oxidized species for the different fuel cell technologies [17,23]

Technology	Fuel feeding used	Oxidized species	Oxidant feeding used	Reduced species
PEMFC	Pure hydrogen, methanol, petrol or natural gas reformat with 40 ppm (Ballard) or 100 ppm (IFC) continuous CO	Hydrogen	Air	Oxygen
AFC	Hydrogen (intolerant to CO ₂ present in the reformat of hydrocarbon molecules)	Hydrogen	Oxygen, air with maximum 10–50 ppm CO ₂	Oxygen
DMFC	Aqueous methanol solution liquid or vapor	Methanol	Air	Oxygen
PAFC	Natural gas reformat with CO < 1%	Hydrogen	Air	Oxygen
MCFC	Partial or total natural gas reformat, direct natural gas	Hydrogen, carbon monoxide	Air with CO ₂ added (recycled from the anode)	Oxygen and carbon dioxide
SOFC	Partial or total natural gas reformat synthetic gas, petrol and diesel reformat, direct natural gas conceivable	Hydrogen, carbon monoxide	Air	Oxygen

6.4.2.1. *Hydrogen*. If hydrogen is, however, the fuel chosen, the anodic line will include a humidifier and a heat exchanger if needed. Depending on the storage solution, hydrogen will have to be compressed or decompressed to the fuel cell operating pressure.

6.4.2.2. *Reformat*. If gasoline or methanol are chosen for storage simplicity, they cannot be supplied directly to the different fuel cell technologies, except for the DMFC. A reforming stage has to be included, to process the fuel into a gas acceptable for the fuel cell.

Sulfur compounds initially present in the fuel have a strong effect on the reforming stage and the fuel cell performances, whatever the fuel cell type. Thus, the stages of sulfur elimination from the fuel must be included (e.g. desulphurization), if the latter contains sulfur compounds in concentration exceeding 10, 100 or 1000 ppm, depending on the technology (see Table 7). As far as the sensitivity to sulfur compounds is concerned, that of the SOFC stack is the lowest, being at 100–1000 ppm level. This together with the simplified fuel processing stage compared to low temperature fuel cells allows SOFC power plants to be eligible for operating with diesel fuel.

The reforming stage of a hydrocarbon produces mainly hydrogen and carbon dioxide, with water and carbon

monoxide in smaller amounts. The fuel and the fuel processing technology determines the amount of these different compounds (see, for example [29]). Thus, at the outlet of a typical methanol–steam reformer about 0.8 mol% or 8000 ppm of CO is obtained. AFC technology, intolerant to CO₂, would need CO₂ and CO (if a platinum-based catalyst is used) purification. An easy (but expensive) solution could be the use for a membrane, like a palladium membrane.

6.4.2.3. *Fuel cell CO-tolerance*. If CO is a fuel for high temperature fuel cells, only very small levels of carbon monoxide can be accepted by low temperature fuel cells continuously and at peak. Above a given amount of carbon dioxide, the performances drop strongly. For example, the presence of 10 ppm carbon monoxide in a fuel stream induces a 4% drop in PEMFC performance (with a Pt-Ru anode catalyst) compared to pure humidified hydrogen operation [30]. A solution to subsequently lower this drop in performance can be through the use of ‘air bleed’ (addition of a small quantity of air at the anode gas inlet) with 2% air bleed and 40 ppm carbon monoxide, the performance drop is subsequently compensated and nearly reaches pure hydrogen levels even with platinum black [30].

Carbon monoxide poisons the anodic platinum-based catalyst. This phenomenon is reversible to a certain extent.

Table 7
Main stack pollutants, ratio of sulfur compounds and carbon monoxide acceptable and associated fuel processing steps as a function of the fuel cell technology

Technology	Pollutants	Ratio of sulfur compounds acceptable/reference	Anode catalyst	Ratio of CO acceptable/reference	Fuel processing steps
PEMFC	Sulfur compounds; CO	<1 ppm	Platinum or platinum-ruthenium	<20 ppm [27], 40–100 ppm with ‘air bleed’	3: reforming, first CO-purification, second CO-purification
AFC	Sulfur compounds, CO ₂ , CO		Platinum/cobalt-based	If Pt: CO < 20 ppm; tolerant with cobalt? CO ₂ (air) < 20–50 ppm	4 or 2: reforming (first CO-purification, second CO-purification), CO ₂ purification
DMFC	Sulfur compounds	Methanol directly	Platinum-ruthenium	Methanol directly	None
PAFC	Sulfur compounds; CO, Hg, Cl ⁻		Platinum	0.7–1 vol.%, 7000–10000 ppm [28]	2: reforming, CO-purification
MCFC	Sulfur compounds	10 ppm [17]	Nickel	100% (combustible)	1: reforming
SOFC	Sulfur compounds	100–1000 ppm [17]	Nickel	100% (combustible)	1: reforming

Except for AFC with non-noble catalysts, PAFC, AFC and PEMFC contain platinum-based catalysts to enhance the hydrogen oxidation. The sensitivity of the same platinum catalyst to carbon monoxide decreases when the temperature increases. Thus, for the PEMFC operating at 80 °C, the carbon monoxide tolerance in a continuous process is <50–100 ppm. For the PAFC operating at 200 °C the carbon monoxide tolerance can reach 1 mol% or 10,000 ppm.

Reformed gas can be directly fed to MCFC and SOFC, but for low temperature fuel cells, at least one or two CO-purification stages have to be included after the reforming stage, in order to reach CO-levels compatible with low temperature fuel cells. Water gas shift (WGS) technology is usually used for the first purification stages. This technology does not allow us to get sufficiently small CO amounts for PEMFC, and a second purification stage has to be added (like for example the preferential oxidation or PrOx of CO technology): For PAFC, only the WGS purification stage is needed.

6.4.2.4. Direct fuel cells. All fuel cells are direct hydrogen fuel cells. The DMFC allows for direct methanol oxidation, but in certain conditions like high dilution of methanol in water and occurs with poorer global fuel cell performances. The direct use of conventional fuel is a very interesting perspective. No fuel processing would be needed. If direct gasoline feeding has not been a success to date—carbon deposition has indeed to be prevented [31], direct pure or diluted methane (purified natural gas or partial reformat) has already been demonstrated for MCFC and SOFC. There is also some work being carried out with higher carbon molecules like ethane and propane, but stack prototypes development have not been reached yet.

Methane from natural gas cannot be directly oxidized in the SOFC and the MCFC, but must be previously reformed into hydrogen and carbon monoxide. Reforming can be carried out with water (steam reforming) or air (partial oxidation), but steam reforming is preferred in current power plants. High amounts of water are usually needed to reform methane, with a current ratio of 2 mol water towards 1 mol methane. In the case of direct methane feeding, two phenomena occur consecutively in the anode compartment: the steam reforming of methane with water into hydrogen and carbon monoxide (stimulated at the operating temperature of the MCFC and the SOFC), and the oxidation of the fuels—H₂ and CO—into water and carbon dioxide.

It is observed that if the fuel conditions the reforming temperature, the stack is decisive in dimensioning the sulfur, carbon monoxide and possibly carbon dioxide removal systems (in the case of AFC).

6.5. Pollutants at the fuel cell stack outlet

The advantage of fuel cells consists mainly in the decrease or even the elimination of contaminant emissions, thus, it is important to evaluate the fuel cell technologies according

to this criterion. For the DMFC, methanol can be found in the outlet gas both on anode and cathode sides. It must be considered to burn this methanol in a burner to avoid dumping it into atmosphere. Whatever the fuel cell technology supplied with pure hydrogen, the only emissions are due to non-consumed hydrogen (which will be subsequently transformed into water in the burner prior to dumping into atmosphere), water and oxygen-poor air. In the case of methanol, gasoline or natural gas fuelled power plants, emissions of carbon monoxide (in very small amounts for low temperature fuel cells) and carbon dioxide, with gasoline or methanol traces, and by-products, such as aldehydes will always exist.

Carbon dioxide and methane emissions allow the evaluation of the production of greenhouse gases. To do so, the vehicle emissions should be evaluated depending on different cycles, which can be carried out by simulation. For the PEMFC methanol power plant, the vehicle application modeling, carried out in the scope of a fuel cell drive train for vehicle projects, forecasts a generation of 80 g CO₂ globally per 100 km in a NMVEG cycle [6].

6.6. Fuel cell stack lifetime maintenance operations

For vehicle application, the stack and power plant lifetime target is 5000 h operation without an important decrease in the performances and without maintenance operations for the stack. In the case of the PEMFC, a lifetime exceeding 5000 h is attained with a tolerance of a voltage drop of 2% over 4000 h in reformat containing 40 ppm of CO [30]. Few data are available concerning the AFC and the DMFC. It seems, however, that both fuel cell types characteristics are less advantageous than the PEMFC, with ca. 2000 h of lifetime. For the DMFC, the principal cause would be the gradual contamination of electrodes and for the alkaline fuel cell, the contamination of electrolyte with carbon dioxide of the air. It would be interesting to have more information about the voltage losses over the lifetime of these technologies. The PAFC, MCFC and SOFC are developed and intended mainly for stationary applications, for which the lifetime target is significantly more stringent than for vehicle applications (40,000 h). However, operating conditions in a continuous mode are much less stringent than in drive application. Lifetimes achieved for stationary applications are not comparable with the dynamic operation in a vehicle.

6.7. Fuel cell stack operating temperature/stack and power plant thermal management/stack problems associated with start, stop, sudden power change

6.7.1. Fuel cell stack operating temperature

The operating temperature determines the starting time and the constraints to evacuate the generated heat. The different fuel cell technologies operating temperatures are presented in Table 3.

PEMFC operates presently at an operating temperature of 80–90 °C. This temperature level allows for stack starting time short enough for vehicle application. However, this temperature is not high enough to easily evacuate the heat generated. An operating temperature of the stack more suitable for evacuation of generated heat should be greater than 120 °C [6]. Current PEMFC with Nafion[®] membrane are not compatible with such high temperatures. As mentioned in Section 5, other types of membranes working at higher operating temperature are currently being investigated.

The DMFC, which is a modified PEMFC, is limited by the Nafion[®] to a maximum operation temperature close to 110 °C under pressure.

The operating temperature range of the AFC is close to that of the PEMFC and is limited by the electrolyte evaporation.

For the PAFC, besides an operation at 200 °C (a little too high for a quick starting), its temperature must always be maintained above 40 °C, which seems to be difficult to realize in a vehicle in different climatic conditions. Pure phosphoric acid is indeed used as an electrolyte for PAFC. This acid has a melting point of 42 °C at atmospheric pressure and greater density as solid than liquid. Therefore, if the stack temperature gets lower than the melting point of the electrolyte, failure may happen in the stack structure.

As far as the MCFC and the SOFC are concerned, the operating temperatures of 650 and 700–1000 °C, respectively (Global Thermoelectric claims even the possibility to start at 500 or 600 °C [8]) make their start-up times probably too long far more suitable for a vehicle application. Nevertheless, these types of fuel cells have been initially developed for stationary applications and their starting times must be optimized to match the vehicle application. It should be added that similar high temperatures are managed in the internal combustion engines. The starting procedure must be especially studied.

By the way, a gasoline reformer operates at about 800 °C and the starting times for a PEMFC power plant with a gasoline reformer is also too long. Even for a methanol supplied PEMFC power plant, in which the reformer operates at ca. 200–300 °C, Sadler et al. [32] have reported a time of hydrogen production over one minute. A strategy oriented to reduce the starting times consists in maintaining the reformer at a high temperature, with a drawback of additional energy consumption. The same strategy can be considered for high temperature fuel cells.

6.7.2. Response to demand variation

In vehicle application, particularly in drive, the fuel cell behavior in dynamic environments is an important criterion. Nevertheless, not all the fuel cell stack technologies can follow instantly the changes in power requirement, and some problems can surge in operating out of the continuous mode. The PEMFC technology presents an adequate behavior in a dynamic mode with response times <0.1 s. However, in the pressurized PEMFC power plant with a methanol or gasoline

reformer, the auxiliaries of the power plant, such as the compressor or reformer, may limit response time.

The alkaline fuel cell, having an operation temperature close to that of the PEMFC would quickly respond to demand variations. Nevertheless, even if Zetek claims to find solutions for electrode flooding and drying problems, demonstration power plants operate usually close to a continuous mode [7].

The DMFC yields better results in dynamic operation than in stationary mode, as reported in the recent study of Argypoulos et al. [33]. These authors have measured response times between 60 and 100 s and have shown an improvement of the voltage response in dynamic operation. They explain this performance improvement by a decrease in methanol permeation rate through the membrane in dynamic operation.

As the operating ranges of PAFC and MCFC technologies are lower as compared with other technologies, the continuous operation is more advantageous.

For the SOFC technology, Achenbach [34] evaluates, by simulation, a response time of 120–300 s depending on the bipolar plate materials. It could also be negative for the lifetime and the stack integrity to operate in dynamic mode at high demand variations. Indeed, variation of the demand provokes local temperature variations, with resulting mechanical stresses in the ceramic structure.

6.8. Stack performance degradation/stack stop of operation, electrolyte loss/mixing of H₂-O₂, etc.

Two other important aspects to be considered in vehicle application are safety and reliability. These aspects can be evaluated in the first stage to identify the causes of reduced performances, hydrogen or electrolyte leaks and stoppage. Examples of risks for the different technologies are given below. It would be interesting to quantify the risk of occurrence of each phenomenon, to seek a solution in order to reduce this risk and to classify each risk depending on its importance by an “operating safety analysis”. This is difficult to realize at a global level, unless a precise power plant is fully analyzed. Therefore, it could not be carried out in the present work.

A cause of PEMFC stoppage is the membrane breaking by pressure difference. AFC with a circulating electrolyte may have power losses through the electrolyte. Loss of DMFC performances can happen through electrode pollution. As for the PEMFC, breaking of the membrane can happen. If the PAFC temperature goes under 40 °C, the fuel cell structure will be destroyed. MCFC and SOFC contain ceramic parts that can be broken through thermal and mechanical shocks and thermal cycling.

7. Conclusion

The PEMFC technology emerges for vehicle application in spite of CO intolerance and thermal management difficulty.

The AFC, in spite of Zetek experiments in London taxis, yields inadequate performances. The DMFC yields low performances, is too expensive and has still technical problems such as the methanol crossover, which reduces its efficiency. The PAFC must be maintained at a temperature exceeding 40 °C, which seems to be incompatible with passenger car application. The high temperature fuel cells (MCFC and SOFC) are interesting because they operate at temperatures close to the reforming conditions and are compatible with carbon monoxide oxidation. The MCFC, however, presents power densities too low and is, therefore, not compact enough for application in private cars. The SOFC yields very interesting performances and high efficiency. Even if the SOFC power plant's thermal management and costs must be seriously studied, this technology has an interesting potential for vehicle application. A decrease in the operating temperature of SOFC from 850–1000 to 600–800 °C would reduce the cost of the stack and auxiliaries of the power plant and simplify the power plant thermal management.

Thus, the technologies, which appear to be the best for vehicle application, are the PEMFC and SOFC technologies. Potential applications of these technologies can be chosen according to the characteristics of starting and response times. In fact, the drive application is the most stringent from this point of view.

The PEMFC technology fuelled with hydrogen offers starting and response times quasi-instantaneous and compatible with the drive application. However, hydrogen PEMFC vehicle presents low range, too long refueling time and non-existent infrastructure. Thus, its current problematic is close to the one of the pure electric vehicle. Concerning the fuel of choice, gasoline may be the one for market introduction of fuel cell vehicle in 2010, since its infrastructure already exists. Progresses have anyhow to be made on gasoline fuel processor system to improve the volume, starting and response time. There are, however, still problems to be solved such as the high cost of the PEMFC stack and the system thermal management.

The SOFC technology offers starting and response times hardly compatible with drive application. It can be considered to maintain the SOFC power plant at its working temperature as well as operation without excessive demand variations, in order to preserve the stack integrity. Its advantage is a simplified reforming, which makes this technology an interesting option for application as an auxiliary power source.

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