

PEM Fuel Cells

Frano Barbir

2.1 Introduction

PEM fuel cells use a proton conductive polymer membrane as electrolyte. PEM stands for Polymer Electrolyte Membrane or Proton Exchange Membrane. Sometimes they are also called polymer membrane fuel cells, or just membrane fuel cells. In the early days (1960s) they were known as Solid Polymer Electrolyte (SPE) fuel cells. This technology has drawn the most attention because of its simplicity, viability, quick start-up, and it has been demonstrated in almost any conceivable application, from powering a cell phone to a locomotive.

At the heart of a PEM fuel cell is a polymer membrane that has some unique capabilities. It is impermeable to gases but it conducts protons (hence Proton Exchange Membrane name). The membrane, which acts as the electrolyte, is squeezed between the two porous, electrically conductive electrodes. These electrodes are typically made out of carbon cloth or carbon fiber paper. At the interface between the porous electrode and the polymer membrane there is a layer with catalyst particles, typically platinum supported on carbon. A schematic diagram of cell configuration and basic operating principles is shown in Figure 2.1 [1,2].

Electrochemical reactions occur at the surface of the catalyst at the interface between the electrolyte and the membrane. Hydrogen, which is fed on one side of the membrane, splits into its primary constituents – protons and electrons. Each hydrogen atom consists of one electron and one proton. Protons travel through the membrane, while the electrons travel through electrically conductive electrodes, through current collectors, and through the outside circuit where they perform useful work and return to the other side of the membrane. At the catalyst sites between the membrane and the other electrode they meet with the protons that went through the membrane and oxygen that is fed on that side of the membrane. Water is created in the electrochemical reaction, and then pushed out of the cell with an excess flow of oxygen. The net result of these simultaneous reactions is current of electrons through an external circuit – direct electrical current.

The hydrogen side is negative and is called the anode, while the oxygen side of the fuel cell is positive and is called the cathode. The electrochemical reactions in

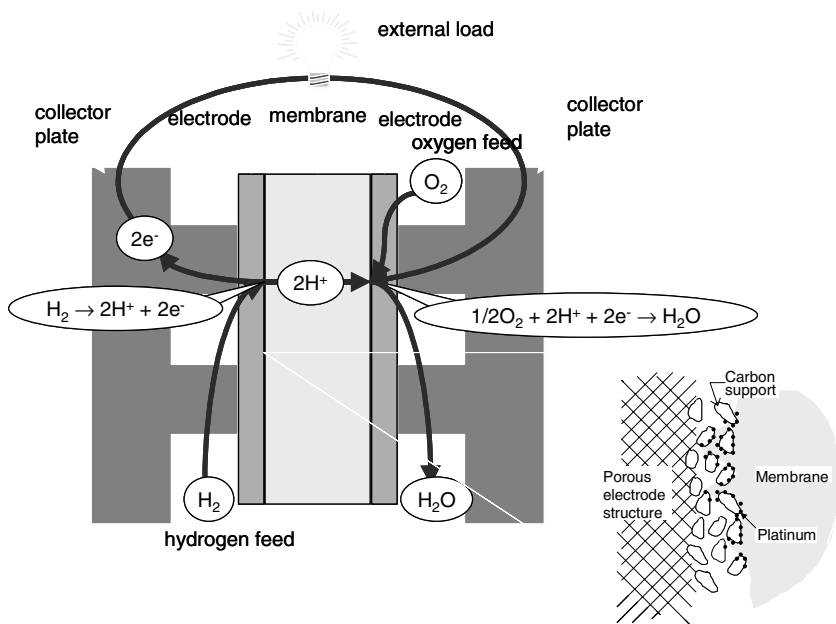
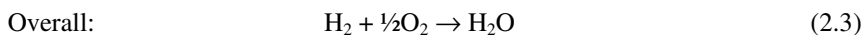
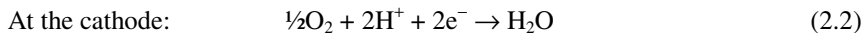


Figure 2.1. The basic principle of operation of a PEM fuel cell [1,2]

fuel cell happen simultaneously on both sides of the membrane – the anode and the cathode. The basic fuel cell reactions are:



The maximum amount of electrical energy generated in a fuel cell corresponds to Gibbs free energy, ΔG , of the above reaction:

$$W_{\text{el}} = -\Delta G \quad (2.4)$$

The theoretical potential of fuel cell, E , is then:

$$E = \frac{-\Delta G}{nF} \quad (2.5)$$

Where n is the number of electrons involved in the above reaction, 2, and F is the Faraday's constant (96,485 Coulombs/electron-mol). Since ΔG , n and F are all known, the theoretical hydrogen/oxygen fuel cell potential can also be calculated:

$$E = \frac{-\Delta G}{nF} = \frac{237,340 \text{ J mol}^{-1}}{2 \cdot 96,485 \text{ As mol}^{-1}} = 1.23 \text{ Volts} \quad (2.6)$$

At 25°C and atmospheric pressure, the theoretical hydrogen/oxygen fuel cell potential is 1.23 Volts.

Assuming that all of the Gibbs free energy can be converted into electrical energy, the maximum possible (theoretical) efficiency of a fuel cell is a ratio between the Gibbs free energy and hydrogen higher heating value, ΔH :

$$\eta = \Delta G / \Delta H = 237.34 / 286.02 = 83\% \quad (2.7)$$

The theoretical (reversible) cell potential is a function of operating temperature and pressure:

$$E_{T,P} = -\left(\frac{\Delta H}{nF} - \frac{T\Delta S}{nF}\right) + \frac{RT}{nF} \ln \left[\frac{a_{H_2} a_{O_2}^{0.5}}{a_{H_2O}} \right] \quad (2.8)$$

where, a stands for activity or the ratio between the partial pressures of reactants (H_2 and O_2) or product (H_2O) and atmospheric pressure (for liquid water product $a_{H_2O} = 1$).

Table 2.1 shows the theoretical fuel cell potential at different temperatures and pressures.

Table 2.1. Theoretical cell potential at different temperatures and pressures [2]

T(K)	Atm.	200 kPa	300 kPa
298.15	1.230	1.243	1.251
333.15	1.200	1.215	1.223
353.15	1.184	1.200	1.209

Actual cell potentials are always smaller than the theoretical ones due to irreversible losses. Voltage losses in an operational fuel cell are caused by several factors such as:

- kinetics of the electrochemical reactions (activation polarization),
- internal electrical and ionic resistance,
- difficulties in getting the reactants to reaction sites (mass transport limitations),
- internal (stray) currents,
- crossover of reactants.

Figure 2.2 shows typical proportion of these losses and the resulting polarization curve [2]. A polarization curve is the most important characteristic of a fuel cell and its performance. It depends on numerous factors such as catalyst loading, membrane thickness and state of hydration, catalyst layer structure, flow field design, operating conditions (temperature, pressure, humidity, flowrates and concentration of the reactant gases), and uniformity of local conditions over the entire active area. Typically, a fuel cell operating at atmospheric pressure should generate more than 0.6 A/cm^2 at 0.6 V , and more than 1 A/cm^2 at 0.6 V when operated pressurized (300 kPa or higher). The typical operating temperature is between 60°C and 80°C , although small fuel cells for portable power are often designed to operate at lower temperatures, and larger automotive fuel cell should preferably be operated at higher temperatures.

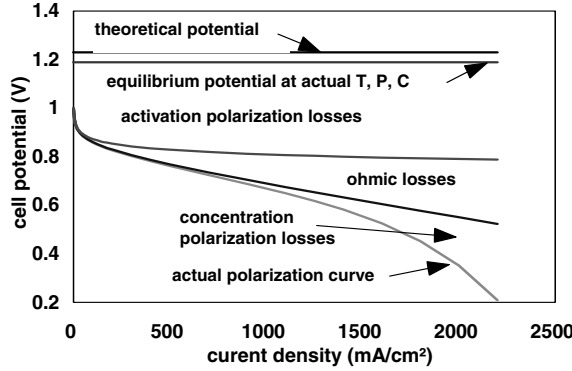


Figure 2.2. Various voltage losses and resulting polarization curve of an operating fuel cell [2]

The fuel cell efficiency, defined as a ratio between the electricity produced and hydrogen consumed is directly proportional to its potential:

$$\eta = \frac{V}{1.482} \quad (2.9)$$

where 1.482 is the thermoneutral potential corresponding to hydrogen's higher heating value. Sometimes, the efficiency is expressed in terms of the lower heating value (LHV):

$$\eta_{\text{LHV}} = \frac{V}{1.254} \quad (2.10)$$

In addition, if some hydrogen is lost (i_{loss}) either due to hydrogen diffusion through the membrane, or due to combining with oxygen that diffused through the membrane or due to internal currents, hydrogen consumption will be higher than that corresponding to generated current, and consequently, the fuel cell efficiency would be somewhat lower than given by equation (2.8) [2]:

$$\eta = \frac{V}{1.482} \frac{i}{(i + i_{\text{loss}})} \quad (2.11)$$

If hydrogen is supplied to the cell in excess of that required for the reaction stoichiometry, this excess will leave the fuel cell unused. In case of pure hydrogen this excess may be recirculated back into the stack so it does not change the fuel cell efficiency (not accounting for the power needed for hydrogen recirculation pump), but if hydrogen is not pure (such as in reformat gas feed) unused hydrogen leaves the fuel cell and does not participate in the electrochemical reaction. The fuel cell efficiency is then:

$$\eta = \frac{V}{1.482} \eta_{\text{fu}} \quad (2.12)$$

where η_{fu} is fuel utilization, which is equal to $1/S_{H_2}$, where S_{H_2} is the hydrogen stoichiometric ratio, *i.e.*, the ratio between the amount of hydrogen actually supplied to the fuel cell and that consumed in the electrochemical reaction.

2.2 PEM Fuel Cell Components and Their Properties

2.2.1 Membrane

A fuel cell membrane must exhibit relatively high proton conductivity, must present an adequate barrier to mixing of fuel and reactant gases, and must be chemically and mechanically stable in the fuel cell environment [3]. Typically, the membranes for PEM fuel cells are made of perfluorocarbon-sulfonic acid ionomer (PSA). This is essentially a copolymer of tetrafluoroethylene (TFE) and various perfluorosulfonate monomers. The best known is Nafion[®] made by Dupont, which uses perfluoro sulfonylfluoride ethyl-propyl-vinyl ether (PSEPVE). Similar materials have been developed and sold either as a commercial or development product by other manufacturers such as Asahi Glass (Flemion[®]), Asahi Chemical (Aciplex[®]), Chlorine Engineers ("C" membrane), and Dow Chemical. W.L. Gore and Associates have developed a composite membrane (GoreSelect[®]) comprising of a Teflon-like component providing mechanical strength and dimensional stability and a perfluorosulfonic acid component providing protonic conductivity.

Nafion[®] membranes come extruded in different sizes and thicknesses. They are marked with a letter N followed by a 3 or 4 digit number. The first two digits represent equivalent weight/100, and the last digit or two is the membrane thickness in mills (1 mill = 1/1000 inch = 0.0254 mm). Nafion[®] is available in several thicknesses, namely 2, 3.5, 5, 7 and 10 mills (50, 89, 125, 178, 250 μ m, respectively). For example, Nafion[®] 117 has an equivalent weight of 1100 and it is 7 mills (0.183 mm) thick.

The main properties of the fuel cell membrane are protonic conductivity, water transport, gas permeation and physical properties such as strength and dimensional stability. All of these properties are directly related to the membrane water content. The water content in a membrane is usually expressed as grams of water per gram of polymer dry weight or the a number of water molecules per sulfonic acid groups present in the polymer, $\lambda = N(H_2O)/N(SO_3H)$. The maximum amount of water in the membrane strongly depends on the membrane (pre)treatment and the state of water used to equilibrate the membrane. A Nafion membrane equilibrated with liquid water (*i.e.*, boiled in water) takes roughly up to 22 water molecules per sulfonate group, while the maximum water uptake from the vapor phase, corresponding to 100% relative humidity in the surrounding gas, is about 14 water molecules per sulfonate group [3].

The protonic conductivity of PFSA membranes is a strong function of water content and temperature. For a fully hydrated membrane ($\lambda = 22$) the protonic conductivity is about 0.1 S cm⁻¹ at room temperature, and at $\lambda = 14$ (membrane equilibrated with water vapor) it is about 0.06 S/cm [4]. Protonic conductivity dramatically increases with temperature and at 80 °C reaches 0.18 S cm⁻¹ for a membrane immersed

in water. Based on these measurements, Springer *et al.* [5] correlated the ionic conductivity (in S cm^{-1}) to water content and temperature with the following expression:

$$\kappa = (0.005139\lambda - 0.00326) \exp \left[1268 \left(\frac{1}{303} - \frac{1}{T} \right) \right] \quad (2.13)$$

Since water plays a critical role in the membrane's primary function, that is proton conduction, maintaining high water content in the membrane is of critical importance. Several mechanisms affect water transport across a polymer membrane and their combination determines the local water content. These mechanisms include the following:

- Water generation on the cathode side at a rate proportional to current generation
- Electroosmotic drag from anode to the cathode as the protons on their way drag one or more water molecules
- Diffusion due to water concentration gradient across the membrane
- Hydraulic permeation due to pressure difference (if any) between the anode and cathode

For a thin membrane water backdiffusion may be sufficient to counteract the anode drying effect due to the electroosmotic drag. However, for a thicker membrane drying may occur on the anode side, particularly at higher current densities.

In principle, the membrane should be impermeable to reactant species, in order to prevent their mixing before they have a chance to participate in the electrochemical reaction. However, due to the membrane's essentially porous structure, its water content and the solubility of hydrogen and oxygen in water, small quantities of gas do permeate through the membrane. Permeability through wet Nafion is another order of magnitude higher, and as expected, hydrogen has one order of magnitude higher permeability than oxygen. Permeability is a linear function of pressure difference and an exponential function of temperature. Typical value for hydrogen permeability at 25°C is about $50 \times 10^{-10} \text{ cm}^3 \text{ cm s}^{-1} \text{ cm}^{-2} \text{ cmHg}^{-1}$ [2]. For a $50 \mu\text{m}$ thick membrane and 300 kPa the loss of hydrogen corresponds to 1.6 mA/cm^2 .

2.2.2 Electrode

A fuel cell electrode is essentially a thin catalyst layer pressed between the ionomer membrane and a porous, electrically conductive substrate. It is the layer where the electrochemical reactions take place. More precisely, the electrochemical reactions take place on the catalyst surface. Since there are three kinds of species that participate in the electrochemical reactions, namely gases, electrons and protons, the reactions can take place on a portion of the catalyst surface where all three species have access to. The reaction zone may be enlarged by either "roughening" the surface of the membrane, and/or by reducing the catalyst particle size, and/or by incorporating ionomer in the catalyst layer.

The most common catalyst in PEM fuel cells for both oxygen reduction and hydrogen oxidation reactions is platinum. In the early days of PEMFC development large amounts of Pt catalyst were used (up to 28 mg cm^{-2}). In the late 1990s with

the use of supported catalyst structures this was reduced to $0.3\text{--}0.4\text{ mg cm}^{-2}$. It is the catalyst surface area that matters, not the weight, so it is important to have small platinum particles (4 nm or smaller) with large surface area finely dispersed on the surface of the catalyst support, typically carbon powders (cca 40 nm) with high mesoporous area ($>75\text{ m}^2\text{ g}^{-1}$). A typical support material is Vulcan XC72R by Cabot, but other carbons such as Black Pearls BP 2000, Ketjen Black Intl. or Chevron Shawinigan have been used [6]. In order to minimize the cell potential losses due to the rate of proton transport and reactant gas permeation in the depth of the electrocatalyst layer, this layer should be made reasonably thin. At the same time, the metal active surface area should be maximized, for which the Pt particles should be as small as possible. For the first reason, higher Pt/C ratios should be selected ($>40\%$ by wt.), however smaller Pt particles and consequently larger metal areas are achieved with lower loading.

In general, higher Pt loading results in voltage gain [7], assuming equal utilization and reasonable thickness of the catalyst layer. However, the key in improving the PEM fuel cell performance is not in increasing the Pt loading, but rather in increasing Pt utilization in the catalyst layer.

The catalyst surface active area may be greatly increased if ionomer is included in the catalyst layer either by painting it with solubilized PFSA in a mixture of alcohols and water or preferably by premixing catalyst and ionomer in the process of forming the catalyst layer. The optimum amount of ionomer in the catalyst layer seems to be around 30% by weight [8].

In principle, there are two ways of preparation of a catalyst layer and its attachment to the ionomer membrane. Such a combination of membrane and catalyst layers is called the membrane electrode assembly or MEA. The first way of preparing an MEA is to deposit the catalyst layer on the porous substrate, so called gas diffusion layer, typically carbon fiber paper or carbon cloth, and then hot-press it to the membrane. The second method of preparing an MEA is application of the catalyst layers directly or indirectly (via a decal process) to the membrane, forming a so-called 3-layer MEA or catalyzed membrane. The porous substrate may be added later, either as an additional step in MEA preparation (in that case a 5-layer MEA is formed) or in a process of stack assembly.

Several methods have been developed for deposition of a catalyst layer on either the porous substrate or the membrane, such as: spreading, spraying, sputtering, painting, screen printing, decaling, electro-deposition, evaporative deposition, and impregnation reduction. There are several manufacturers of MEAs, such as Dupont, 3M, Johnson Matthey, W.L. Gore & Associates and (previously dmc² and Degussa). Their manufacturing processes are typically trade secrets.

At present there are no alternative cathode electrocatalysts to platinum. Some platinum alloy electrocatalysts prepared on traditional carbon black supports offer a 25 mV performance gain compared to Pt electrocatalysts. However, only the more stable Pt-based metal alloys, such as PtCr, PtZr or PtTi can be used in PEMFC, due to dissolution of the base metal by the perfluorinated sulfonic acid in the electrocatalyst layer and membrane [6]. The focus of the continued search for the elusive electrocatalyst for oxygen reduction in acid environments should be on development of materials with required stability, and greater activity than Pt.

2.2.3 Gas Diffusion Layer

The required properties of the gas diffusion layer follow from its functions [9]:

- It must be sufficiently porous to allow flow of both reactant gases and product water (note that these fluxes are in opposite direction). Depending on the design of the flow field, diffusion in both through plane and in plane is important.
- It must be both electrically and thermally conductive, again both through plane and in plane. Interfacial or contact resistance is typically more important than bulk conductivity.
- Since the catalyst layer is made of discrete small particles the pores of the gas diffusion layer facing the catalyst layer must not be too big.
- It must be sufficiently rigid to support the “flimsy” MEA. However, it must have some flexibility to maintain good electrical contacts.

These somewhat conflicting requirements are best met by carbon fiber based materials such as carbon-fiber papers and woven carbon fabrics or cloths. These diffusion media are generally made hydrophobic in order to avoid flooding in their bulk. Typically, both cathode and anode gas diffusion media are PTFE-treated. A wide range of PTFE loadings have been used in PEMFC diffusion media (5% to 30%), most typically by dipping the diffusion media into an PTFE solution followed by drying and sintering. In addition, the interface with the adjacent catalyst layer may also be fitted with a coating or a microporous layer to ensure better electrical contacts as well as efficient water transport into and out of the diffusion layer. This layer (or layers) consists of carbon or graphite particles mixed with PTFE binder. The resulting pores are between 0.1 and 0.5 μm , thus much smaller than the pore size of the carbon fiber papers (20–50 μm) [9].

2.2.4 Bipolar Plates

The bipolar collector/seperator plates have several functions in a fuel cell stack. Their required properties follow from their functions, namely [10]:

- they connect cells electrically in series – therefore they must be electrically conductive;
- they separate the gases in adjacent cells – therefore they must be impermeable to gases;
- they provide structural support for the stack – therefore they must have adequate strength, yet they must be lightweight;
- they conduct heat from active cells to the cooling cells – therefore they must be thermally conductive;
- they typically house the flow-field channels – therefore they must be conformable.

In addition, they must be corrosion resistant in the fuel cell environment, yet they must not be made out of “exotic” and expensive materials. In order to keep the

cost down not only must the material be inexpensive, but also the manufacturing process must be suitable for mass production.

In general, two families of materials have been used for PEM fuel cell bipolar plates, namely graphite-composite and metallic. The bipolar plates are exposed to a very corrosive environment inside a fuel cell (pH 2–3 and temperature 60–80°C). The typical metals such as aluminum, steel, titanium or nickel would corrode in fuel cell environment, and dissolved metal ions would diffuse into the ionomer membrane, resulting in lowering of the ionic conductivity and reducing the fuel cell life. In addition, a corrosion layer on the surface of a bipolar plate would increase electrical resistance. Because of these issues, metallic plates must be adequately coated with a non-corrosive yet electrically conductive layer, such as graphite, diamond-like carbon, conductive polymer, organic self-assembled polymers, noble metals, metal nitrides, metal carbides, indium doped tin oxide, *etc.* Carbon composite bipolar plates have been made using thermoplastics (polypropylene, polyethylene, or polyvinylidene fluoride) or thermoset resins (phenolic, epoxies and vinyl esters) with fillers (such as carbon/graphite powder, carbon black or coke-graphite) and with or without fiber reinforcements. These materials are typically chemically stable in fuel cell environments, although some thermosets may leach and consequently deteriorate. Depending on the rheological properties of these materials they are suitable for compression molding, transfer molding, or injection molding.

One of the most important properties of the fuel cell bi-polar plates is their electrical conductivity. Typical bulk electrical conductivity of graphite-composite bipolar plates is between 50 and 200 S cm⁻¹. Pure graphite has a conductivity of 680 S cm⁻¹, and metallic plates have typically several orders of magnitude higher electrical conductivity. One should distinguish between the bulk and total conductivity/resistivity, the latter including bulk and interfacial contact components. In an actual fuel cell stack contact (interfacial) resistance is more important than bulk resistance. For example, a 3 mm thick molded graphite/composite plate with bulk resistivity as high as 8 mΩcm would result in 2.4 mV voltage loss at 1 A/cm², while resistance resulting from the interfacial contacts, such as between the bipolar plate and the gas diffusion layer, may be several times higher [9–11].

2.3 Stack Design Principles

A fuel cell stack consists of a multitude of single cells stacked up so that the cathode of one cell is electrically connected to the anode of the adjacent cell. In this way exactly the same current passes through each of the cells. Note that the electrical circuit is closed with both electron current passing through solid parts of the stack (including the external circuit) and ionic current passing through the electrolyte (ionomer), with the electrochemical reactions at their interfaces (catalyst layers).

The bipolar configuration is the best for larger fuel cells since the current is conducted through relatively thin conductive plates, thus it travels a very short distance through a large area (Figure 2.3). This causes minimum electroresistive losses, even with a relatively poor electrical conductor such as graphite (or graphite polymer mixtures). However, for small cells it is possible to connect the edge of

one electrode to the opposing electrode of the adjacent cell by some kind of connector. This is applicable only to very small active area cells because current is conducted in the plane of very thin electrodes, thus traveling relatively long distance through a very small cross-sectional area.

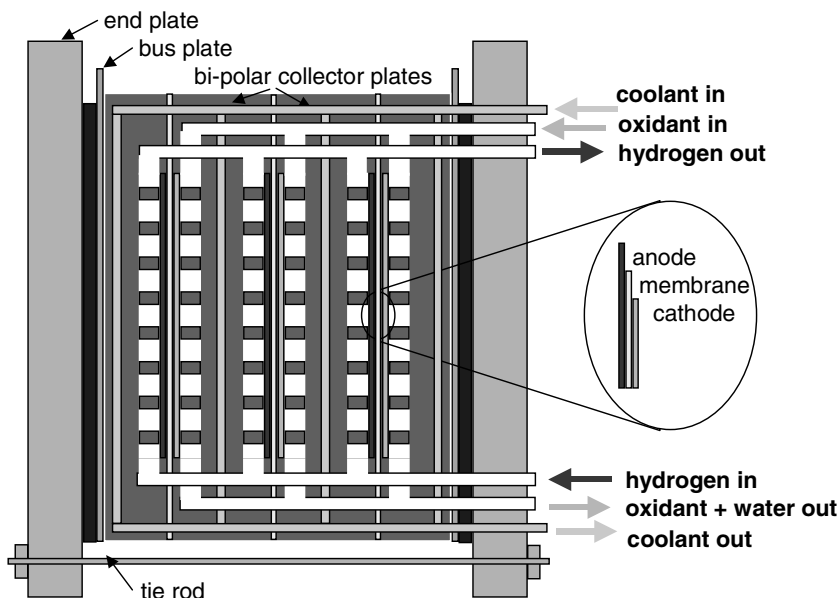


Figure 2.3. Fuel cell stack schematic [2,12]

The key aspects of a fuel cell stack design are the following [2]:

- Uniform distribution of reactants to each cell
- Uniform distribution of reactants inside each cell
- Maintenance of required temperature in each cell
- Minimum resistive losses (choice of materials, configuration, uniform contact pressure)
- No leak of reactant gases (internal between the cells or external)
- Mechanical sturdiness (internal pressure including thermal expansion, external forces during handling and operation, including shocks and vibrations)

Since the fuel cell performance is sensitive to flowrate of the reactants, it is absolutely necessary that each cell in a stack receives approximately the same amount of reactant gases. Uneven flow distribution would result in uneven performance of each cell. Uniformity is accomplished by feeding each cell in the stack in parallel through a manifold that can be either external or internal. External manifolds can be made much bigger to ensure uniformity, they result in a simpler stack design, but they can only be used in a cross-flow configuration and are in general difficult to seal. Internal manifolds are more often used in PEM fuel cell design not only because of better sealing but also because they offer more versatility in gas flow configuration.

The flow pattern through the stack can be either a “U” shape, where the inlet and outlet are at the same side of the stack and the flows in the inlet and outlet manifolds are in opposite direction, or a “Z” shape where the inlets and outlets are on opposite sides of the stack and the flows in the inlet and outlet manifolds are parallel to each other (Figure 2.4) [13]. If properly sized both should result in uniform flow distribution to individual cells. Stacks with more than a hundred cells have been successfully built.

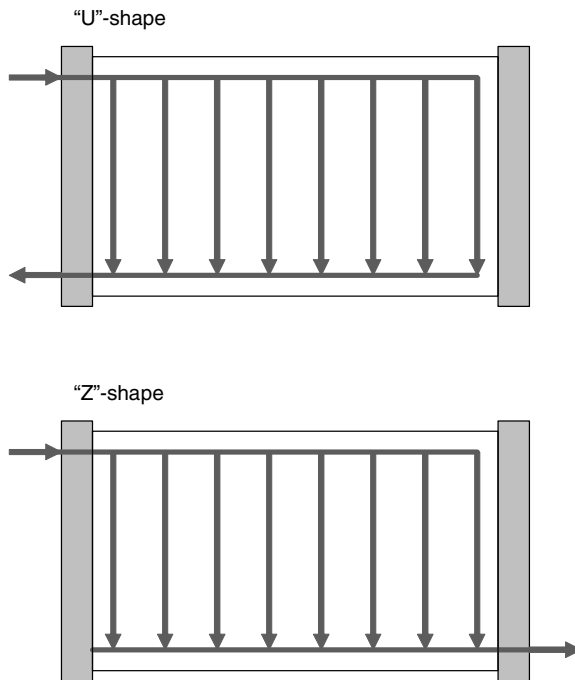


Figure 2.4. Stack flow configurations [13]

Once the reactant gases enter the individual cell they must be distributed over the entire active area. This is typically accomplished through a flow field, which may be in a form of channels covering the entire area in some pattern or porous structures. The following are the key flow field design variables [2]:

- flow field shape
- flow field orientation
- configuration of channels
- channels shape, dimensions and spacing
- pressure drop through the flow field.

One of the most common configurations of the flow field channels is in a serpentine fashion either as a single channel (for smaller active area) or as multiple channels that wind up through the entire active area connecting the inlet to the outlet manifolds. In another configuration, the inlet and outlet channels are not

connected but intertwined in an interdigitated fashion, thus forcing the flow through the gas diffusion layer. In both configurations, there are several modifications tried in the fuel cell stacks. Typically, the flow field configuration is a well-kept secret by the stack manufacturers. CFD modeling is a great tool for design of the fuel cell flow field and has been increasingly used [14–18].

In order to maintain the desired temperature inside the cells, the heat generated as a byproduct of the electrochemical reactions must be taken away from the cells and from the stack. Different heat management schemes may be applied such as [2]:

- *Cooling with a coolant flowing between the cells.* Coolant may be de-ionized water, antifreeze coolant or air. Cooling may be arranged between each cell, between the pair of cells (in such a configuration one cell has the cathode and the other cell has the anode next to the cooling arrangement), or between a group of cells (this is feasible only for low power densities since it results in higher temperatures in the center cells). Equal distribution of coolant may be accomplished by the manifold arrangement similar to that of reactant gases. If air is used as a coolant equal distribution may be accomplished by a plenum.
- *Cooling with coolant at the edge of the active area (with or without fins).* The heat is conducted through the bipolar plate and then transferred to the cooling fluid, typically air. In order to achieve a relatively uniform temperature distribution within the active area, the bipolar plate must be very good thermal conductor. In addition, the edge surface may not be sufficient for heat transfer and fins may need to be employed. This method results in a much simpler fuel cell stack, fewer parts, but it has heat transfer limitations, and is typically used for low power outputs.
- *Cooling with phase change.* Coolant may be water or another phase change medium. Use of water simplifies the stack design since water is already used in both anode and cathode compartments.

The individual components of a fuel cell stack, namely MEAs, gas diffusion layers and bipolar plates must be somehow held together with sufficient contact pressure to (i) prevent leaking of the reactants between the layers, and (ii) to minimize the contact resistance between those layers. This is typically accomplished by sandwiching the stacked components between the two end plates connected with several tie-rods around the perimeter or in some cases through the middle. Other compression and fastening mechanisms may be employed too, such as snap-in shrouds or straps [2].

2.4 System Design

A fuel cell stack is obviously the heart of a fuel cell system, however, without the supporting equipment the stack itself would not be very useful. The fuel cell system typically involves the following subsystems:

- oxidant supply (oxygen or air),
- fuel supply (hydrogen or hydrogen-rich gas),

- heat management,
- water management,
- power conditioning, and
- instrumentation and controls.

The simplest way to supply hydrogen from a tank to a fuel cell is in the dead-end mode. Such a system would only require a preset pressure regulator to reduce the pressure from the stack to the fuel cell operating pressure. The long term operation in a dead-end mode may be possible only with extremely pure gases, both hydrogen and oxygen. Any impurities present in hydrogen will eventually accumulate in the fuel cell anode. This also includes water vapor that may remain (in case when the back-diffusion is higher than the electroosmotic drag, which may be the case with very thin membranes and when operating at low current densities. In addition, nitrogen may diffuse from the air side until an equilibrium concentration is established. In order to eliminate this accumulation of inerts and impurities, purging of the hydrogen compartment may be required. This may be programmed either as a function of cell voltage or as a function of time.

If purging of hydrogen is not possible or preferred due to safety, mass balance or system efficiency reasons, excess hydrogen may be flowed through the stack ($S > 1$) and unused hydrogen returned to the inlet, either by a passive (ejector) or an active (pump or compressor) device. In either case, it is preferred to separate and collect any liquid water that may be present at the anode outlet. The amount of liquid water to be collected depends on operating conditions and membrane properties. In thinner membranes, backdiffusion may be higher than the electroosmotic drag, and some of the product water may exit the stack at the anode side.

Hydrogen typically must be humidified up to 100% relative humidity prior to entering the fuel cell stack, in order to avoid drying of the membrane due to electroosmotic drag. In this case a humidifier/heat exchanger is needed at the stack inlet. Hydrogen may be humidified by water injection, and simultaneously or subsequently heated to facilitate evaporation of water, or by membrane humidification.

In hydrogen-air systems, air is supplied by a fan or a blower (for low pressure systems) or by an air compressor for pressurized systems. In the former case the exhaust from the fuel cell is open directly into the environment, while in a pressurized system, pressure is maintained by a preset pressure regulator at the fuel cell exhaust. In either case, a fan, or a blower or a compressor is run by an electric motor that requires electrical power, and thus represents power loss or parasitic load, which may have a significant effect on the system efficiency. Air typically has to be humidified before entering the fuel cell stack. Various humidification schemes may be employed such as:

- bubbling of gas through water
- direct water or steam injection
- exchange of water (and heat) through a water permeable medium
- exchange of water (and heat) on an adsorbent surface (enthalpy wheel).

At the stack outlet, typically there is some liquid water that may be easily separated from the exhaust air, in a simple, off-the-shelf gas/liquid separator. Water

collected at the exhaust may be stored and reused, either for cooling and/or for humidification.

Water and heat are the byproducts of the fuel cell operation, and the supporting system must include the means for their removal. Both water and heat from the fuel cell stack may be at least partially re-used, for example for humidification of the reactant gases. Water and heat handling may be integrated into a single subsystem if deionized water is used as a stack coolant. In that case water removes the heat from the stack and the same water and heat are used to humidify the reactant gases. The remaining heat has to be discarded to the surroundings through a heat exchanger, for hydrogen-air systems that is typically a radiator. The amount of heat to be discarded must be calculated from the stack and humidifier energy balances. The size of the radiator heat exchanger depends on the temperature difference between the coolant and the ambient air. For that reason, it is preferred to operate the fuel cell system at a higher temperature, for systems where the size of the components is critical. However, the operating pressure and water balance must be taken into account when deciding on the operating temperature. It should be noted that smaller stacks may be air cooled. In that case a fan replaces the coolant pump. Reuse of waste heat collected by air as coolant is not practical, but it may be convenient to blow the warm exhaust over the metal hydride tanks.

For very small power outputs it is possible to design and operate a fuel cell with a passive air supply, relying only on natural convection due to concentration gradients. Such a fuel cell typically has either the front of the cathode directly exposed to the atmosphere, therefore without the bipolar plates, or in bi-polar configuration the cathode flow field is sideways opened to the atmosphere. In either case an oxygen concentration gradient is formed between the open atmosphere and the catalyst layer where oxygen is being consumed in the electrochemical reaction. The performance of such fuel cells is typically not limited only by the oxygen diffusion rate, but also by water and heat removal, both dependent on the temperature gradient. The maximum

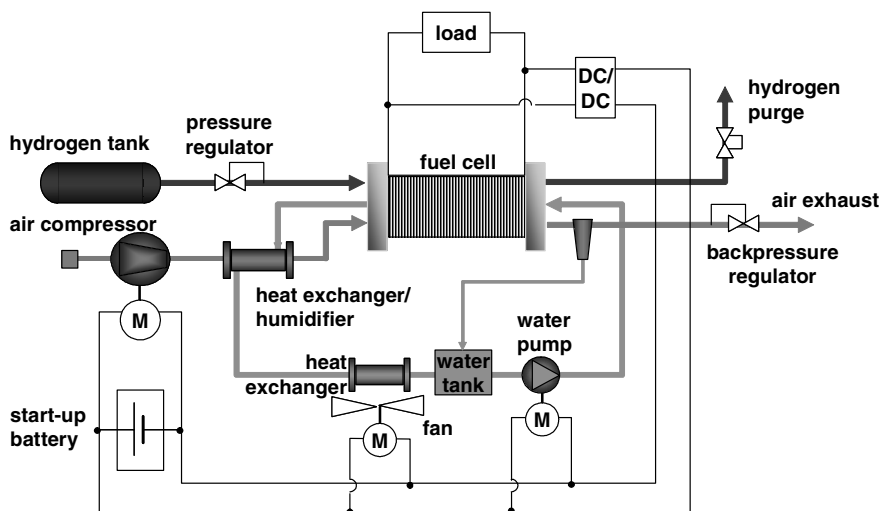


Figure 2.5. An example of a complete hydrogen-air fuel cell system [19]

the fuel processor in Figure 2.6 is shown as a box, while actually it consists of a series of reactors and heat exchangers necessary for the reforming process. There are several issues that must be addressed in the design of such an integrated system, such as CO content in the produced reformat gas, transient behavior, water balance, reforming efficiency, parasitic power needed for the reforming process, controls, *etc.*

The efficiency of the fuel cell system is lower than the fuel cell efficiency given by equation (2.11); it must also include the efficiency of the reforming process, including the preferential oxidation efficiency, the efficiency of power conditioning and the parasitic power requirements (for both fuel cell and fuel processor subsystems). The overall system efficiency is then:

$$\eta_{\text{sys}} = \eta_{\text{ref}} \eta_{\text{PROX}} \eta_{\text{fuel}} \eta_{\text{FC}} \eta_{\text{PC}} \quad (2.14)$$

where the efficiency of power conditioning, η_{PC} , also includes the parasitic power losses, through a coefficient ξ , which is defined as a ratio between power needed to run the parasitic load and fuel cell gross power:

$$\eta_{\text{PC}} = \eta_{\text{DC}} \left(1 - \frac{\xi}{\eta_{\text{DCaux}}} \right) \quad (2.15)$$

where η_{DC} and η_{DCaux} are the efficiency of DC/AC or DC/DC power conversions for both the main load and parasitic power, respectively.

The achievable efficiency of such systems is about 40%. The systems using hydrogen as fuel may have an efficiency around 50% and those that use pure oxygen as oxidant may have an efficiency above 50%.

2.5 Fuel Cell Applications

Fuel cells can generate power from a fraction of a watt to hundreds of kilowatts. Because of this, they may be used in almost every application where local electricity generation is needed. Applications such as automobiles, buses, utility vehicles, scooters, bicycles, submarines have been already demonstrated. Fuel cells are ideal for distributed power generation, at a level of individual homes, buildings or a community, offering tremendous flexibility in power supply. In some cases both power and heat produced by a fuel cell may be utilized, resulting in very high overall efficiency. As a backup power generator, fuel cells offer several advantages over either internal combustion engine generators (noise, fuel, reliability, maintenance) or batteries (weight, lifetime, maintenance). Small fuel cells are attractive for portable power applications, either as replacement for batteries (in various electronic devices and gadgets) or as portable power generators.

Fuel cell and fuel cell system design are not necessarily the same for each of these applications. On the contrary, each application, besides power output, has its own specific requirements, such as efficiency, water balance, heat utilization, quick startup, long dormancy, size, weight, fuel supply, *etc.*

2.5.1 Automotive Applications

All major car manufacturers have demonstrated prototype fuel cell vehicles and announced plans for production and commercialization. The major drivers for development of automotive fuel cell technology are their efficiency, low or zero emissions, and fuel that could be produced from indigenous sources rather than being imported. The main obstacles for fuel cell commercialization in automobiles are the cost of fuel cells and the cost and availability of hydrogen.

The fuel cell may be connected to the propulsion motor in several ways [2], namely:

- 1) Fuel cell is sized to provide all the power needed to run the vehicle. A battery may be present but only for startup (such as a 12V battery). This configuration is typically possible only with direct hydrogen fuel cell systems. A system with a fuel processor would not have as good dynamic response. Also, a small battery would not be sufficient to start up a system with a fuel processor.
- 2) Fuel cell is sized to provide only the base load, but the peak power for acceleration of the vehicle is provided by the batteries or similar peaking devices (such as ultracapacitors). This may be considered as a parallel hybrid configuration since the fuel cell and the battery operate in parallel – the fuel cell provides cruising power, and the battery provides peak power (such as for acceleration). The presence of a battery in the system results in much faster response to load changes. The vehicle can be started without preheating of the fuel cell system, particularly the fuel processor, and operated as a purely battery-electric vehicle until the fuel cell system becomes operational. A battery allows for recapturing of the braking energy, resulting in a more efficient system. The disadvantages of having the battery are extra cost, weight and volume.
- 3) Fuel cell is sized only to re-charge the batteries. The batteries provide all the power needed to run the vehicle. This may be considered as serial hybrid configuration (fuel cell charges the battery and battery drives the electric motor). The same advantages and disadvantages of having a battery apply as for the parallel hybrid configuration. The fuel cell nominal power output depends on how fast the batteries would have to be recharged. A smaller battery would have to be recharged faster and would result in a larger fuel cell.
- 4) Fuel cell serves only as an auxiliary power unit, *i.e.* another engine is used for propulsion, but the fuel cell is used to run the entire or a part of the vehicle electrical system [20]. This may be particularly attractive for trucks, since it would allow operation of an air-conditioning or refrigeration unit while the vehicle is not moving without the need to run the main engine.

In general, a fuel cell propulsion engine is more efficient than a comparable internal combustion engine. However, the efficiency of fuel cells vs. internal combustion engine should not be compared at their most favorable operating point. These two technologies are intrinsically different and have very different efficiency-power characteristics. While an internal combustion engine has its maximum efficiency at or near its maximum power [21], a fuel cell system has its maximum efficiency at partial load [22] (Figure 2.7). Because of this, the efficiency of a hydrogen fueled fuel cell propulsion system in a typical driving schedule, where an automobile

engine operates most of the time at partial load, can be about twice that of an internal combustion engine [23–25]. The hydrogen fuel cell system efficiency in a driving schedule can be in the upper 40s and above 50%. The efficiency of a fuel cell propulsion system with an onboard fuel processor is lower than the efficiency of a hydrogen fuel cell system, but still higher than the efficiency of an internal combustion engine. The fuel cell efficiency advantage diminishes if both a fuel cell or an internal combustion engine are used in a hybrid configuration.

One of the biggest problems related to hydrogen use in passenger vehicles is its on-board storage. Hydrogen, can be stored as compressed gas, as a cryogenic liquid or in metal hydrides. Tanks for compressed gaseous hydrogen are bulky, even if hydrogen is compressed to 450 bar. It takes about 40–50 liters of space to store 1 kg of hydrogen. The amount of fuel to be stored onboard depends on the vehicle fuel efficiency and required range.

Automotive fuel cells must survive and operate in extreme weather conditions (-40 to +40°C). This requirement has a tremendous effect on system design. Survival and start-up in extremely cold climates requires specific engineering solutions, such as use of antifreeze coolant and water management. Water cannot be completely eliminated from the system, because water is essential for the membrane ionic conductivity.

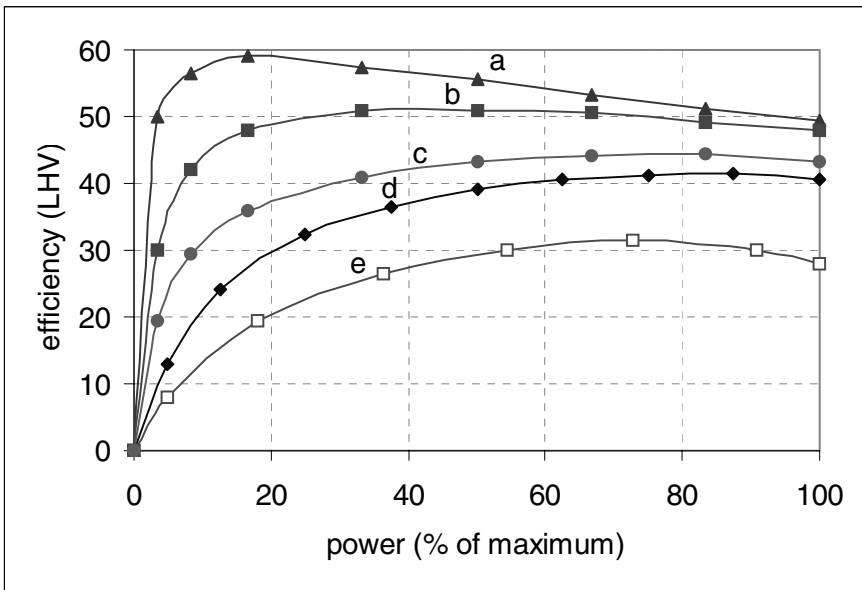


Figure 2.7. Comparison of the efficiency of fuel cells and internal combustion engines [2]

- a) fuel cell system operating at low pressure and low temperature
- b) fuel cell system operating at high pressure and high temperature
- c) fuel cell system with an on-board fuel processor
- d) compression ignition internal combustion engine (diesel)
- e) spark ignition internal combustion engine (gasoline) (compiled from [21] and [22])

The fuel cell heat rejecting equipment (radiator and/or condenser) must be sized for heat rejection in extremely hot weather (typically from 32 to 40°C [21]). Although a fuel cell system is more efficient than an internal combustion engine it has similar or larger cooling loads. More importantly, because of the fuel cell's low operating temperature (60 to 80°C) the heat rejection equipment is typically much larger than that for a comparable internal combustion engine [21,26].

Water balance requirements result in additional cooling loads [21,26]. Although water is produced in a fuel cell, water is needed for humidification of reactant gases and for fuel processing (in the case of an on-board fuel processor) and it has to be reclaimed from the exhaust gases.

Buses for city and regional transport are considered to be the most likely types of vehicles for an early market introduction of fuel cell technology. Buses require more power than passenger automobiles, typically about 250 kW or more. They operate in a more demanding operating regime with frequent starts and stops. Nevertheless, the average fuel economy of a bus fuel cell system is roughly 15% better than that of a diesel engine [27]. Buses are almost always operated in a fleet, and refueled in a central facility. This makes refueling with hydrogen much easier. In addition, storing larger quantities of hydrogen on board (typically above 20 kg) is less of a problem. Fuel cell buses typically store hydrogen in composite compressed gas cylinders at 250 to 300 bar, located on the roof. Because hydrogen is much lighter than air, the roof location is considered to be very safe.

Utility vehicles, such as fork-lifts, material handling industrial vehicles, airport ground support tow vehicles, lawn maintenance vehicles, golf carts and airport people movers, may be another early adapter of the fuel cell technology. This application is not as demanding as the passenger vehicles or the buses. The competing technology are typically the batteries, most often the lead acid batteries, that require frequent and lengthy charging and pose significant maintenance problems. Early demonstrations of fuel cell powered utility vehicles have shown that such vehicles offer lower operating cost, reduced maintenance, lower down-time, and extended range [28].

Scooters and bicycles may be a significant market for fuel cell technologies, particularly in developing countries. Despite the stringent requirements relating to weight, size and low cost, fuel cells have been successfully demonstrated in various scooters and bicycles [28]. The power requirement is considerably less than for the automobiles – up to 3 kW for scooters and up to 1 kW for bicycles. Although the range may be smaller than for automobiles too, the volume of hydrogen storage is one of the critical issues. Some prototypes were demonstrated with direct methanol fuel cell systems. The fuel cells for scooters and bicycles are almost always air-cooled. The refueling issue of these vehicles in mass markets is equally as complex as the issue of automobile refueling. However, because of significantly smaller quantities of hydrogen to be stored onboard, additional options are possible, such as distribution of metal hydride tanks or home refueling devices (probably electrolyzers).

2.5.2 Stationary Power Applications

Although development and demonstrations of fuel cells in automobiles usually draws more attention, applications for stationary power generation offer even greater market opportunity. The drivers for both market sectors are similar – higher efficiency and lower emissions. The system design for both applications is also similar in principle. The main differences are in the choice of fuel, power conditioning, and heat rejection [29]. There are also some differences in requirements for automotive and stationary fuel cell systems. For example, size and weight requirements are very important in automotive applications, but not so significant in stationary applications. The acceptable noise level is lower for stationary applications, especially if the unit is to be installed indoors. The fuel cell itself of course does not generate any noise, noise may be coming from air and fluid handling devices. Automobile systems are expected to have a very short start-up time (fraction of a minute), while the startup of a stationary system is not time limited, unless operated as a backup or emergency power generator. Both automotive and stationary systems are expected to survive and operate in extreme ambient conditions, although some stationary units may be designed for indoor installation only. And finally, the automotive systems for passenger vehicles are expected to have a life-time of 3000 to 5000 operational hours, systems for buses and trucks somewhat longer, but the stationary fuel cell power systems are expected to operate for 40000 to 800000 hours (five to ten years).

Stationary fuel cell power systems will enable the concept of distributed generation, allowing the utility companies to increase their installed capacity following the increase in demand more closely, rather than anticipating the demand in huge increments by adding gigantic power plants. Presently, obtaining the permissions and building a conventional power plant have become very difficult tasks. Fuel cells, on the other hand, do not need special permitting and may be installed virtually everywhere – inside the residential areas, even inside the residential dwellings. To the end users the fuel cells offer reliability, energy independence, “green” power, and, ultimately, lower cost of energy.

Stationary fuel cells may be used in different applications, namely:

- As the only power source, thus competing with or replacing the grid, or providing electricity in the areas not covered by the grid.
- As a supplemental power source working in parallel with the grid covering either the base load or the peak load.
- For both power and heat cogeneration in either power load following or heat load following mode.
- In combined systems with intermittent renewable energy sources (such as photovoltaics or wind turbines) generating power in periods when these energy sources cannot meet the demand.
- As a backup or emergency power generator providing power when the grid (or any other primary power source) is down.

Accordingly, the fuel cell system, and particularly its power conditioning and interconnect module, may be designed as [2]:

- Grid parallel – allowing power from the grid to the consumer when needed, but not allowing power from the fuel cell back to the grid. The fuel cell system may be sized to provide most of the consumer's energy needs but the grid is used to cover the short-term demand peaks. Such a system essentially does not need batteries (except for start-up when the grid is down), and does not need interconnect standards.
- Grid interconnected – allowing power flow in both directions, namely power from the grid to the consumer when needed, and power from the fuel cell back to the grid. Such a system may be designed as load following or as constant power, since excess fuel cell power can be exported to the grid. Of course, this design option requires interconnect standards.
- Standalone – providing power without grid. The system must be capable of load following. Very often a sizeable battery bank is used to enable load following.
- Backup or emergency generator – the system must be capable of quick startup and is also often combined with the batteries or other peaking device. Batteries are typically superior for low power/low duration backup power, but a fuel cell system becomes competitive for higher power (several kW) and longer duration (over 30 minutes). A backup power system may be equipped with an electrolyzer-hydrogen generator and hydrogen storage [30]. In this case the unit generates its own fuel during periods when electricity from the grid is available.

Commercialization of stationary fuel cells greatly depends on their economics, which besides the selling price includes their annual (not maximum) efficiency, capacity factor (depending on application), lifetime, maintenance, but most of all on a ratio between the prices of electricity and natural gas. In order for a stationary fuel cell to be feasible, the ratio between the prices of electricity and natural gas must be larger than the reciprocal of its annual efficiency (*i.e.* > 3 and preferably > 4). The prices of electricity and natural gas vary with time and from region to region. The economics of stationary fuel cells may be improved if the waste heat is utilized in a cogeneration manner. Some residential fuel cells are being developed to operate in a heat load following mode.

2.5.3 Portable Power Applications

A portable power system is a small grid-independent electric power unit ranging from a few watts to roughly one kilowatt, which serves mainly the purpose of convenience rather than being a primarily a result of environmental or energy-saving considerations [31]. These devices may be divided into two main categories:

- 1) battery replacements, typically well under 100 W
- 2) portable power generators, up to 1 kW

The key feature of small fuel cells to be used as battery replacements is the running time without recharging. Obviously, by definition, the size and weight are also important. Power units with either significantly higher power densities or larger energy storage capacities than those of existing secondary batteries may find applications in portable computers, communication and transmission devices,

power tools, remote meteorological or other observation systems, and in military gadgets. Besides the size of the fuel cell itself, the critical issue is the fuel and its storage. Hydrogen, although being a preferred fuel for PEM fuel cells is rarely used because of the bulkiness or weight of its storage, even in the small quantities required by those small devices. Hydrogen may be stored in room temperature metal hydride storage tanks. Some chemical hydrides offer higher energy density, however, they must be equipped with suitable reactors where hydrogen is released in a controlled chemical reaction [32]. Most of portable fuel cells use methanol as fuel, or more precisely aqueous methanol solutions, either directly (so called direct methanol fuel cells) or via microreformers.

The military market is particularly attractive as it often may be a sympathetic early adopter of new technologies, willing to accept high prices and limited performance if other, application-specific, requirements can be met (such as low noise, low thermal signature, long duration both in operation and dormant, size and weight, safety) [33]. Some examples of early military fuel cell products or prototypes include battery chargers, soldier power, telecommunications, navigation systems, computers, various tools, exoskeletons, auxiliary power unit for vehicles, unmanned aerial vehicles, small autonomous robot vehicles, unattended sensors and munitions, and ocean sensors and transponders [33].

Development of small fuel cells for portable power applications have resulted in a myriad of stack configurations. Some stacks are miniaturized replicas of the larger automotive or stationary power fuel cells with the same components, MEAs, gas diffusion layers, bipolar plates and end plates. Some use a planar configuration where the cells are connected with conductive strips. Recently, microfluidic cells manufactured on silicon based chips have emerged [34, 35]. The fuel cell systems for these applications are extremely simplified. The simplicity of the system is more important than the cell/stack size. The power density generated is often below 0.1 W/cm^2 . These cells/stacks do not need active cooling, those using hydrogen mainly operate in a dead-end mode, and air is often supplied passively.

2.6 Summary

PEM fuel cells are the most attractive of all the fuel cell types for many applications due to their simplicity, quick startup, load following capabilities, efficiency, modularity and versatility. An overwhelming majority of fuel cell related patents and publications refer to PEM fuel cells. Only for large ($>250 \text{ kW}$) stationary power applications, high temperature fuel cells have significant advantage.

Although the PEM fuel cells have been demonstrated in numerous applications, the key barriers to their widespread commercial use are:

- Nonexistence of hydrogen fuel infrastructure, and difficulties related to hydrogen storage,
- Relatively high cost of early fuel cell prototypes and products,
- Insufficient lifetime for some applications (particularly stationary power generation).

Commercialization of fuel cells, particularly for transportation and stationary electricity generation markets, must be accompanied by commercialization of hydrogen energy technologies, *i.e.* technologies for hydrogen production, distribution and storage. In other words, hydrogen must become a readily available commodity (not as a technical gas but as an energy carrier) before fuel cells can be fully commercialized. Fuel cells running on natural gas may also be a viable option but only if their efficiency and economics are better than that of conventional technologies for electricity generation. On the other hand, fuel cells have many unique properties, such as high energy efficiency, no emissions, no noise, modularity, and potentially low cost, which may make them attractive in many applications even with limited hydrogen supply. Fuel cells may very well become a driver for development of hydrogen energy technologies. Fuel cells will change the way energy is converted to useful power and are likely one of those powerful technologies that could create the next revolution – the energy revolution, similar to the steam engine that created the industrial revolution, the Ford Model T that created automobile revolution or the computer that created the information revolution.

2.7 References

1. F. Barbir, Fuel Cell Tutorial, presented at Future Car Challenge Workshop, Dearborn, MI, October 25–26, 1997
2. F. Barbir, *PEM Fuel Cells: Theory and Practice*, Elsevier Academic Press, New York, 2005
3. S. Gottesfeld and T.A. Zawodzinski, Polymer Electrolyte Fuel Cells, in R.C. Alkire, H. Gerischer, D.M. Kolb, and C.W. Tobias (Eds.) *Advances in Electrochemical Science and Engineering*, Volume 5, Wiley-VCH, New York, 1997
4. T.A. Zawodzinski, Jr., T.E. Springer, J. Davey, R. Jestel, C. Lopez, J. Valerio, and S. Gottesfeld, A Comparative Study of Water Uptake By and Transport Through Ionomeric Fuel Cell Membranes, *Journal of the Electrochemical Society*, Vol. 140, 1993, p. 1981–1985
5. T.E. Springer, T.A. Zawodzinski, and S. Gottesfeld, Polymer Electrolyte Fuel Cell Model, *Journal of the Electrochemical Society*, Vol. 138, No. 8, pp. 2334–42, 1991.
6. T.R. Ralph and M.P. Hogarth, Catalysis for Low Temperature Fuel Cells, Part I: The Cathode Challenges, *Platinum Metals Review*, Vol. 46, No. 1, pp.3–14, 2002
7. H.A. Gasteiger, W. Gu, R. Makharia and M.F. Mathias, Catalyst utilization and mass transfer limitations in the polymer electrolyte fuel cells, *Electrochemical Society Meeting*, Orlando, September, 2003
8. T.A. Zawodzinski, Jr., M. Eikerling, L. Pratt, R. Antonio, R. Tommy, M. Hickner, J. McGrath, Membranes for Operation Above 100°C, in *Proc. 2002 National Laboratory R&D Meeting DOE Fuel Cells for Transportation Program* (Golden, CO, May 9, 2002). [M.F. Mathias, J. Roth, J. Fleming and W. Lehnert, Diffusion media materials and characterization, in W. Vielstich, A. Lamm, and H.A. Gastegier (Eds.) *Handbook of Fuel Cells, Fundamentals, Technology and Applications*, Vol. 3 Fuel Cell Technology and Applications, pp. 517–537, John Wiley & Sons, Ltd., New York, 2003.
10. F. Barbir, J. Braun, and J. Neutzler, Properties of Molded Graphite Bi-Polar Plates for PEM Fuel Cells, *International Journal on New Materials for Electrochemical Systems*, No. 2, pp. 197–200, 1999

11. V. Mishra, F. Yang and R. Pitchumani, Electrical contact resistance between gas diffusion layers and bi-polar plates in a PEM fuel cell, *Proc. 2nd Int. Conf. Fuel Cell Science, Engineering and Technology*, Rochester, NY, 2004
12. T.N. Veziroglu and F. Barbir, *Hydrogen Energy Technologies*, UNIDO - Emerging Technologies Series, United Nations Industrial Development Organisation, Vienna, Austria, 1998
13. J.-H. Koh, K. Seo, C. G. Lee, Y. -S. Yoo, and H. C. Lim, Pressure and Flow Distribution in Internal Gas Manifolds of a Fuel Cell Stack, *Journal of Power Sources*, Vol. 115, 2003, pp. 54–65.
14. V. Gurau, F. Barbir, and H. Liu, Two-Dimensional Model for the Entire PEM Fuel Cell Sandwich, in *Proton Conduction Membrane Fuel Cells II*, S. Gottesfeld and T.F. Fuller (eds.), *Proc. Vol. 98–27*, pp. 479–503, The Electrochemical Society, Pennington, NJ, 1999.
15. H. Naseri-Neshat, S. Shimpalee, S. Dutta, W.K. Lee and J.W. Van Zee, Predicting the effect of gas-flow channel spacing on current density in PEM fuel cells, *Advanced Energy Systems* Vol. 39, pp. 337–350, ASME, 1999
16. S.Um, C.-Y. Wang and K. S. Chen, 2000, “Computational fluid dynamics modeling of proton exchange membrane fuel cells,” *J. Electrochem. Soc.*, Vol. 147, pp. 4485–4493, 2000.
17. L. You and H. Liu, A two-phase flow and transport model for the cathode of PEM fuel cells, *Int. J. Heat and Mass Transfer*, 45, pp. 2277–2287, 2002
18. S. Shimpalee, S. Greenway, D. Spuckler and J. W. Van Zee, Predicting water and current distributions in a commercial-size PEMFC, *J. Power Sources*, Vol. 135, pp. 79–87, 2004
19. F. Barbir, M. Nadal, and M. Fuchs, Fuel Cell Powered Utility Vehicles, in Buchi, F. (editor), *Proc. of the Portable Fuel Cell Conference* (Lucerne, Switzerland, June 1999), pp. 113–126.
20. J. Tachtler, T. Dietsch, and G. Goetz, Fuel Cell Auxiliary Power Unit – Innovation for the Electric Supply of Passenger Cars, SAE Paper No. 2000-01-0374, in *Fuel Cell Power for Transportation 2000* (SAE SP-1505) (SAE, Warrendale, PA, 2000), pp. 109–117.
21. D.A. Masten and A. D. Bosco, System Design for Vehicle Applications: GM/Opel, in W. Vielstich, A. Lamm, and H. Gasteiger (editors), *Handbook of Fuel Cell Technology – Fundamentals, Technology and Applications*, Vol. 4 (J. Wiley, New York, 2003), pp. 714–724.
22. R. Stone, Competing Technologies for Transportation, in G. Hoogers (editor), *Fuel Cell Technology Handbook* (CRC Press, Boca Raton, FL, 2003).
23. C.E. Thomas, B. D. James, F. D. Lomax, Jr., and I. F. Kuhn, Jr., Fuel Options for the Fuel Cell Vehicle: Hydrogen, Methanol or Gasoline? *International Journal of Hydrogen Energy*, Vol. 25, No. 6, 2000, pp. 551–568.
24. Well-to-Wheel Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems, North American Analysis. Report by General Motors in cooperation with Argonne National Laboratory, BP Amoco, ExxonMobil and Shell, 2001.
25. Weiss, M. A., J. B. Heywood, E. M. Drake, A. Schafer, and F. F. AuYeung, *On the Road in 2020. A Life-Cycle Analysis of New Automobile Technologies* (Massachusetts Institute of Technology, Boston, 2000).
26. Fronk, M. H., D. L. Wetter, D. A. Masten, and A. Bosco, PEM Fuel Cell System Solutions for Transportation, SAE Paper No. 2000-01-0373, in *Fuel Cell Power for Transportation 2000* (SAE SP-1505) (SAE, Warrendale, PA, 2000), pp. 101–108.
27. Hoogers, G., Automotive Applications, in G. Hoogers (editor), *Fuel Cell Technology Handbook* (CRC Press, Boca Raton, FL, 2003).

28. M. Croper, Fuel Cell Market Survey: Niche Transport, *Fuel Cell Today*, Article 823, June 2004: http://www.fuelcelltoday.com/FuelCellToday/FCTFiles/FCTArticleFiles/Article_823_NicheTransport0604.pdf (accessed February 2005)
29. F. Barbir, System Design for Stationary Power Generation, in W. Vielstich, A. Lamm, and H. Gasteiger (editors), *Handbook of Fuel Cell Technology – Fundamentals, Technology and Applications*, Vol. 4 (J. Wiley, New York, 2003), pp. 683–692.
30. F. Barbir, T. Maloney, T. Molter, and F. Tombaugh, Fuel Cell Stack and System Development: Matching Market to Technology Status, in *Proc. 2002 Fuel Cell Seminar* (Palm Springs, CA, November 18–21, 2002), pp. 948–951.
31. G. Hoogers, Portable Applications, in G. Hoogers (editor), *Fuel Cell Technology Handbook* (CRC Press, Boca Raton, FL, 2003).
32. A. Heinzel and C. Hebling, Portable PEM Systems, in W. Vielstich, A. Lamm, and H. Gasteiger (editors), *Handbook of Fuel Cell Technology – Fundamentals, Technology and Applications*, Vol. 4 (J. Wiley, New York, 2003), pp. 1142–1151.
33. S. Geiger and D. Jollie, Fuel Cell Market Survey: Military Applications, *Fuel Cell Today*, Article 756, April 2004: http://www.fuelcelltoday.com/FuelCellToday/FCTFiles/FCTArticleFiles/Article_756_MilitarySurvey0404.pdf (accessed February 2005)
34. K. Shah, W. C. Shin, and R. S. Besser, A PDMS Micro Proton Exchange Membrane Fuel Cell by Conventional and Non-Conventional Microfabrication Techniques, *Sensors and Actuators B: Chemical*, Vol. 97, No. 2–3, 2004, pp. 157–167.
35. Y. Yamazaki, Application of MEMS Technology to Micro Fuel Cells, *Electrochimica Acta*, Vol. 50, No. 2–3, 2004, pp. 659–662.

Fuel Cell Technology

Reaching Towards Commercialization

Sammes, N. (Ed.)

2006, XIV, 298 p. 139 illus., Hardcover

ISBN: 978-1-85233-974-6