

FUEL CELL TECHNOLOGY AND APPLICATION

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Abstract

This paper provides a survey of fuel cell technology and application. A description of fuel cell operating principles is followed by a comparative analysis of the current fuel cell technology together with issues concerning various fuels. Appropriate applications for current and perceived potential advances of fuel cell technology are discussed.

1. INTRODUCTION

In order to move towards a sustainable existence in our critically energy dependent society there is a continuing need to adopt environmentally sustainable methods for energy production, storage, and conversion.

The use of fuel cells in both stationary and mobile power applications can offer significant advantages for the sustainable conversion of energy. Benefits arising from the use of fuel cells include efficiency and reliability, as well as economy, unique operating characteristics, and planning flexibility and future development potential. By integrating the application of fuel cells, in series with renewable energy storage and production methods, sustainable energy requirements may be realised.

2. FUEL CELL FUNDAMENTALS

2.1 Description

A fuel cell is conventionally defined as an “electrochemical cell which can continuously convert the chemical energy of a fuel and an oxidant to electrical energy by a process involving an essentially invariant electrode-electrolyte system” [1]. For a hydrogen/oxygen fuel cell the inputs are hydrogen (fuel) and oxygen (oxidant) and the only outputs are dc power, heat, and water.

When pure hydrogen is used no pollutants are produced, and the hydrogen itself can be produced from water using renewable energy sources such that the system is environmentally benign. In practice hydrogen is the best fuel for most applications. In addition to hydrogen some fuel cells can also use carbon monoxide and natural gas as a fuel. In these

reactions, carbon monoxide reacts with water producing hydrogen and carbon dioxide, and natural gas reacts with water producing hydrogen and carbon monoxide, the hydrogen that is produced is then used as the actual fuel.

2.2 Electrochemistry

The basic physical structure of all fuel cells consists of an electrolyte layer in contact with an anode and cathode electrode on either side of the electrolyte. The electrolyte provides a physical barrier to prevent the direct mixing of the fuel and the oxidant, allows the conduction of ionic charge between the electrodes, and transports the dissolved reactants to the electrode. The electrode structure is porous, and is used to maximise the three-phase interface between the electrode, electrolyte and the gas/liquid, and also to separate the bulk gas phase and the electrolyte. The gas/liquid ionisation or de-ionisation reactions take place on the surface of the electrode, and the reactant ions are conducted away from or into the three-phase interface [2]. A schematic representation of a fuel cell with the reactant/product gases and the ion conduction flow directions through the cell is shown in Fig.1.

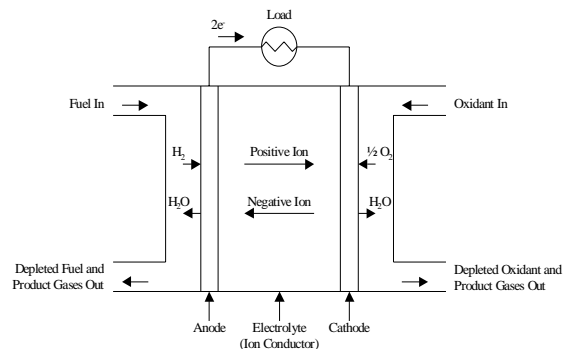


Fig.1 Basic working concepts [2]

In theory a fuel cell is capable of producing an electric current so long as it supplied with fuel and an oxidant. In practice the operational life of the fuel cell is finite, and fuel cell performance will gradually deteriorate over a period of time as the electrode and electrolyte age. However, because fuel cells operate with no moving parts, highly reliable systems are achieved [3].

2.3 Efficiency

The thermal efficiency of the fuel cell can be defined as the percentage of useful electrical energy produced relative to the heat that would have been obtained through the combustion of the fuel (enthalpy of formation). In the ideal case, the maximum efficiency (or thermodynamic efficiency) of a fuel cell operating irreversibly can be expressed as the percentage ratio of Gibbs free energy over the enthalpy of formation, that is,

$$Efficiency = \frac{\Delta G}{\Delta H}$$

where ΔG is change in Gibbs free energy and ΔH is the enthalpy of formation of the reaction. For the hydrogen/oxygen fuel cell the thermodynamic efficiency limit at the higher heating value (HHV) is equal to 83% [3].

In practice the efficiency of the fuel cell can be expressed in terms of the percentage ratio of operating cell voltage relative to the ideal cell voltage as

$$Efficiency = 0.83 \frac{V_{cell}}{V_{ideal}}$$

where V_{cell} is the actual voltage of the cell and V_{ideal} is the voltage obtained from Gibbs free energy in the ideal case. The 0.83 is from the thermodynamic limit (HHV). In the non-ideal case the actual operating voltage is less than the ideal voltage because of the irreversible losses associated with the fuel cell electrochemistry. There are three primary irreversible losses that result in the degradation of fuel cell performance and these are activation polarisation, ohmic polarisation, and concentration polarisation [1-3]. Fig.2 illustrates the effects of the irreversible losses on cell voltage for a low temperature, hydrogen/oxygen fuel cell.

Activation polarisation is caused by limited reaction rates at the surface of the electrodes, and is dominant at low current density and increases marginally with an increase in current density.

Ohmic polarisation is caused by the resistance to the flow of ions in the electrolyte and to the flow of electrons through the electrode materials. This loss is directly proportional to the current density.

Concentration polarisation is caused by a loss of concentration of the fuel or oxidant at the surface of the electrodes. These losses are present over the entire current density range but become prevalent at high limiting currents where it becomes difficult to provide enough reactant flow to the cell reaction sites.

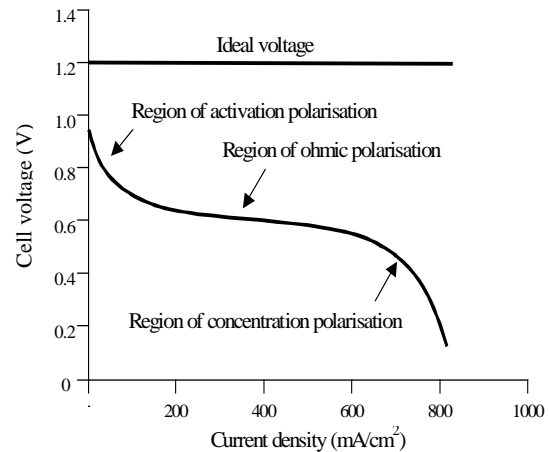


Fig.2 Ideal and actual voltage/current curves of a low temperature hydrogen/oxygen fuel cell (From [2,3])

2.4 Advantages

The main advantages of fuel cells are:

Efficiency - Fuel cells are generally more efficient than combustion engines as they are not limited by temperature as is the heat engine.

Simplicity - Fuel cells are essentially simple with few or no moving parts. High reliability may be attained with operational lifetimes exceeding 40,000 hours (the operational life is formally over when the rated power of the fuel cell is no longer satisfied) [3-5].

Low emissions - Fuel cells running on direct hydrogen and air produce only water as the by-product.

Silence - The operation of fuel cell systems are very quiet with only a few moving parts if any. This is in strong contrast with present combustion engines.

Flexibility - Modular installations can be used to match the load and increase reliability of the system.

2.5 Disadvantages

The principal disadvantages of fuel cells, however, are the relatively high cost of the fuel cell, and to a lesser extent the source of fuel. For automotive applications a cost of US\$10 to \$50 per kW and an operation life of 4000 hours is required in order to compete with current internal combustion engine technology. For stationary combined heat and power systems a cost of US\$1000 per kW and an operation life of 40,000

hours is required [5,6]. The current cost of a fuel cell system is around US\$3000 per kW for large systems with additional costs required for the heat exchanger in the combined heat and power systems. The cost of fuel cells will be brought down with mass manufacture and costs of US\$100 per kW have been predicted as the production of fuel cells expand over the following few years [5].

3. FUEL CELL CLASSES

There are five primary classes of fuel cells, identified by their electrolyte, which have emerged as viable systems [2]. Although the most common classification of fuel cells is by the type of electrolyte used, there are always other important differences as well. Each fuel cell class differs in the materials of construction, the fabrication techniques, and the system requirements. The potential use for different applications is inherent in the main characteristics of each fuel cell class [2].

Solid Oxide (SOFC): The solid oxide fuel cell operates between 500-1000°C. The electrolyte in this fuel cell is a solid, nonporous metal oxide and the charge carriers are oxygen ions. The electrolyte always remains in a solid state adding to the inherent simplicity of the fuel cell. The solid ceramic construction of the cell, can minimise hardware corrosion, allows for flexible design shapes, and is impervious to gas crossover from one electrode to the other. Due to the high temperature operation, high reaction rates are achieved without the need for expensive catalysts and also gases such as natural gas can be internally reformed without the need for fuel reforming. Unfortunately the high operating temperature limits the materials selection and a difficult fabrication processes results. In addition the ceramic materials used for the electrolyte exhibit a relatively low conductivity, which lowers the performance of the fuel cell.

Polymer Electrolyte Membrane (PEMFC): The polymer electrolyte membrane fuel cell operates at 50-100°C. The electrolyte in this fuel cell is a solid ion exchange membrane used to conduct protons. Hardware corrosion and gas crossover are minimised as a result of the solid electrolyte and very high current densities as well as fast start times have been realised for this cell. However due to the low temperature operation, catalysts (mostly platinum) are needed to increase the rate of reaction. In addition heat and water management issues are not easily overcome in a practical system, and tolerance for CO is low.

Alkaline (AFC): The alkaline fuel cell operates between 50-250°C. The electrolyte in this fuel cell is KOH, and can be either mobile or retained in a matrix material. Many catalysts can be used in this fuel cell,

an attribute that provides development flexibility. The AFC has excellent performance on hydrogen and oxygen compared to other candidate fuel cells. The major disadvantage of this fuel cell is that it is very susceptible to CO₂ and CO poisoning and hence its use with reformed fuels and air is limited.

Phosphoric Acid (PAFC): The phosphoric acid fuel cell operates at 200°C with phosphoric acid (100%) used for the electrolyte. The matrix universally used to retain the acid is silicon carbide, and the catalyst is Platinum. The use of concentrated acid (100%) minimises the water vapour pressure so water management in the cell is not difficult. The cell is tolerant to CO₂ and the higher temperature operation is of benefit for co-generation applications. The main limitation of the PAFC is the lower efficiency realised in comparison with other fuel cells.

Molten Carbonate (MCFC): The molten carbonate fuel cell operates at 600°C. The electrolyte in this fuel cell is usually a combination of alkali carbonates retained in a ceramic matrix. At the high temperature of operation the alkali carbonates form a highly conductive molten salt, with carbonate ions providing ionic conduction. The high reaction rates remove the need for noble metal catalysts and gases such as natural gas can be internally reformed without the need for a separate unit. In addition the cell can be made of commonly available sheet metals for less costly fabrication. One feature of the MCFC is the requirement of CO₂ at the cathode for efficient operation. The main disadvantage of the MCFC is the very corrosive electrolyte that is formed, which impacts on the fuel cell life, as does the high temperature operation.

In addition to the five primary fuel classes, there are two more classes of fuel cells that are not distinguished by their electrolyte. These are the Direct Methanol Fuel Cell (DMFC), distinguished by the type of fuel used, and the Regenerative Fuel Cell (RGF) distinguished by its method of operation.

4. FUELS FOR FUEL CELLS

4.1 Fuel Requirements

In theory, any substance that is capable of being chemically oxidised at a sufficient rate at the anode of the fuel cell may be used as a fuel. In the same sense, any substance that is capable of being reduced at the cathode of the fuel cell at a sufficient rate may be used as an oxidant [2].

In practice, hydrogen is the best fuel for most applications. The low-temperature fuel cells such as the AFC, PEMFC, and PAFC, are electrochemically

constrained to hydrogen fuel use only, while the high-temperature fuel cells such as MCFC and the SOFC, in addition to hydrogen can also use carbon monoxide and natural gas as a fuel. In these reactions, carbon monoxide reacts with water producing hydrogen and carbon dioxide, and natural gas reacts with water producing hydrogen and carbon monoxide, the hydrogen that is produced is then used as the fuel.

Similarly, oxygen is the most common oxidant because it is readily and economically available from air.

4.2 Advantages of Hydrogen

The wide spread use of hydrogen as the fuel choice for fuel cells has the following benefits [1,5]:

- High electrochemical reactivity when suitable catalysts are used, and high energy content (kJ/kg),
- The oxidation of hydrogen is a simple and environmentally benign reaction that makes zero emissions power systems possible,
- The source of energy production is not constrained to any particular fuel type and hence provides the basis for a rapid progress towards a sustainable transportation and electricity system,
- An increase in retail price competition as a result of the many fuel sources available.

4.3 Sources of Hydrogen

Unfortunately, hydrogen does not occur naturally as a gaseous fuel and must be produced from another source. Potential sources of hydrogen include, such as fossil fuels (coal, oil, or natural gas), a variety of chemical intermediates (refinery products, ammonia, methanol), and alternative resources such as bio-mass, bio-gas, and waste materials. Hydrogen can also be produced by water electrolysis, which uses electricity to split hydrogen and oxygen elements [6]. The electricity for the water electrolysis can be generated from conventional sources or from renewable sources. In the longer term, hydrogen generation could be based on photo-biological or photochemical methods [7].

4.4 Fuel Processing

Some fuel processing will almost always be required in order to produce useful hydrogen rich gas from another source. Most of the hydrogen currently produced on the industrial scale is through the steam reforming of natural gas, which produces carbon dioxide as a by product. While this method of hydrogen production is generally the most economic, it is not sustainable in the long term and can serve only as an intermediate step, as is the same for all fossil fuels. However the sustainable production of

hydrogen can be achieved with current technology through bio-fuels or by the electrolysis of water using renewable energy sources such as hydro-power, solar energy or wind energy [4,8].

4.5 Hydrogen Economy

The emergence of a true hydrogen economy, based upon hydrogen for energy storage, distribution, and utilisation would be a major advantage for the wide spread application of fuel cells. Although there is already an existing manufacturing, distribution, and storage infrastructure of hydrogen, it is limited. The infrastructure costs associated with a large scale hydrogen distribution, is often cited as the major disadvantage for the wide spread use of hydrogen as “a major world fuel and energy vector” [3]. In addition there are concerns that because of the relatively low density of hydrogen it is not viable for energy storage, particularly in mobile applications, and there is also concern in regard to the safety of hydrogen [5].

It can be argued however, that with good integration practices for both distributed fuel cell power supplies and mobile power applications, natural gas or off peak electricity can initially be used for hydrogen production, removing the initial requirement for the large infrastructure costs associated with a hydrogen distribution system. In this case, the hydrogen can be produced as needed, in quantities to match the incremental growth of fuel cells applications. The reforming of natural gas, and the use of electricity from coal fired power plants can be used as an intermediate step and does not constrain the hydrogen use to a particular fuel type [5].

4.6 Hydrogen storage

In addition the storage of hydrogen, although not limited to, can be achieved in the simple form of a compressed gas. While the use of compressed hydrogen gas in stationary applications presents a viable option there is concern that the insufficient density of storing hydrogen as a compressed gas limits its inclusion in mobile applications. This is however not necessarily the case, as is illustrated with the design approach of using compressed hydrogen gas storage in the ultra light fuel cell vehicles termed hypercars [5].

Finally, the safe storing hydrogen as a compressed gas are in many ways less stringent than the safe storing of alternative fuels such as methanol, petrol, or natural gas. The hydrogen gas would be stored in extremely strong carbon fibre cylinders. Because of the rapid diffusion of hydrogen any spill will dissipate quickly. Hydrogen is also non-toxic and requires a four fold higher concentration than petrol to ignite [5].

Additional methods of hydrogen storage include [3]:

1. Storage as a cryogenic liquid,
2. Storage as a reversible metal hydride,
3. The use of metal hydride reactions with water, and
4. The use of carbon nano-fibers.

The first three methods of hydrogen storage are currently available and are generally well understood processes. The fourth method, which uses carbon nano-fibres for hydrogen storage is not yet practical although considerable efforts are being invested into making this a feasible technology.

5. FUEL CELL APPLICATIONS

As a result of the inherent size flexibility of fuel cells, the technology may be used in applications with a broad range of power needs. This is a unique feature of fuel cells and their potential application ranges from systems of a few watts to megawatts. Table 1 illustrates some typical fuel cell applications for the different fuel cell types.

Table 1. Typical Applications [3]

TYPICAL APPLICATIONS	Portable electronics equipment.			Cars, boats, and domestic CHP.			Distributed power generation, CHP, and buses.		
MAIN ADVANTAGES	Higher energy density to batteries, faster recharging.			Potential for zero emissions, higher efficiency.			Higher efficiency, less pollution, quiet operation.		
POWER(W)	1	10	100	1K	10K	100K	1M	10M	
APPLICATION RANGE FOR FUEL CELL CLASS	<p>The diagram shows the application ranges for five fuel cell classes across a power spectrum from 1W to 10M. ACF (Alkaline Fuel Cell) ranges from 10W to 100W. PEMFC (Proton Exchange Membrane Fuel Cell) ranges from 1W to 100W. SOFC (Solid Oxide Fuel Cell) ranges from 100W to 100K. MFC (Micro Fuel Cell) ranges from 100W to 10M. PAFC (Phosphoric Acid Fuel Cell) ranges from 100K to 10M.</p>								

Note: CHP - Combined Heat and Power

Fuel cell applications may be classified as being either mobile or stationary applications. The mobile applications primarily include transportation systems and portable electronic equipment while stationary applications primarily include combined heat and power systems for both residential and commercial needs. In the following, fuel cell applications for transportation, portable electronic equipment, and combined heat and power systems are addressed.

5.1 Transportation Applications

Cars

All the world leading car manufacturers have designed at least one prototype vehicle using fuel cells. Some of the car manufacturers (Toyota, Ford) have chosen to feed the fuel cell with methanol, while others have

preferred to use pure hydrogen (Opel has used liquid hydrogen, General Motors has stored hydrogen in hydride form). In the short term there is a general trend for the car manufacturers to use reformed methanol as the fuel type for the fuel cell. However, over in the long term hydrogen remains the fuel of choice for the majority of the car manufacturers.

Since 1994, Daimler-Benz working in collaboration with Ballard, built a series of PEMFC powered cars. The first of such vehicles was fuelled with hydrogen, and in 1997 Daimler-Benz released a methanol fuelled car with a 640 km range. Plans are to offer a commercial vehicle by 2004 [2].

In 1996, Toyota built a hydrogen-fuelled (metal hydride storage) fuel cell/battery hybrid passenger car, which was followed, in 1997 by a methanol-fuelled car built on the same RAV4 platform. Renault and PSA-Peugeot Citroën are currently working on an improved design based on the results obtained from the FEVER prototype. General Motors, Volkswagen, Volvo, Honda, Chrysler, Nissan, and Ford have also announced plans to build prototype PEMFC cars operating on hydrogen, methanol, or gasoline. International Fuel Cells, Plug Power, and Ballard Power Systems are each participating in separate programs to build 50 to 100 kW fuel cell systems for cars [2].

NECAR Program

The NECAR program, initiated in 1994, was designed in 4 phases leading to 4 prototypes of electric vehicles. The aim of this program was to show the feasibility of such a vehicle and then to improve the technology during each of the design phases.

The latest in the series is NECAR 4, which uses the 5-seater Mercedes Class A vehicle as the platform. Incorporating a PEMFC using hydrogen stored in a cryogenic tank, it offers a maximum speed of 145 km/h and an operating range of 450 km.

A compressor maintains the fuel cell under pressure. Air and hydrogen pass through a humidifier and a thermal exchanger before enter to the fuel cell. A condenser recovers the water produced by the fuel cell. An air radiator evacuates excessive heat. NECAR 4 can accelerate from 0 to 60 km/h in 6 seconds.

Buses

In 1993, Ballard Power Systems demonstrated a 10 m light-duty transit bus with a 120 kW fuel cell system, followed by a 200 kW, 12 meter heavy-duty transit bus in 1995. These buses use no traction batteries and operate on compressed hydrogen as the on-board fuel.

In 1997, Ballard provided 205 kW PEMFC units for a small fleet of hydrogen-fuelled, full-size transit buses for demonstrations in Chicago, Illinois, and Vancouver, British Columbia. The marketing phase is envisaged for 2002 [2].

5.2 Portable Electronic Equipment

In addition to large-scale power production, miniature fuel cells could replace batteries that power consumer electronic products such as cellular telephones, portable computers, and video cameras. Small fuel cells could be used to power telecommunications satellites, replacing or augmenting solar panels. Micro-machined fuel cells could provide power to computer chips. Finally, minute fuel cells could safely produce power for biological applications, such as hearing aids and pacemakers [6]. Unlike transportation applications where fuel cells are competing with the internal combustion engines to indirectly produce a mechanical output, in portable electronic equipment fuel cells are in competition with devices such as batteries to produce an electrical output. As a result fuel cells can offer a viable alternative to batteries and several low power fuel cells are currently being manufactured for this application.

5.3 Combined Heat and Power Systems

The primary stationary application of fuel cell technology is for the combined generation of electricity and heat, for buildings, industrial facilities or stand-by generators. Because the efficiency of fuel cell power systems is nearly unaffected by size, the initial stationary plant development has focused on the smaller, several hundred kW to low MW capacity plants. "The plants are fuelled primarily with natural gas, and operation of complete, self-contained, stationary plants has been demonstrated using PEMFC, AFC, PAFC, MCFC, SOFC technology" [2].

6. CONCLUSION

In summary the significant areas identified for further research relate to the storage of hydrogen, the integration of fuel cells with renewable energy sources, and the modelling and methodology for system optimisation and design.

The primary barrier to the commercialisation of fuel cell applications is the associated manufacturing cost. Currently the cost of fuel cell systems is greater than that of similar, already available products, mainly because of small scale production and the lack of economies of scale.

The best fuel for fuel cells is hydrogen and another barrier is fuel flexibility. In stationary applications

there is a case for using natural gas or electricity from conventional sources, as an intermediate step to reduce the large infrastructure costs associated with implementing a hydrogen economy.

In mobile applications particularly transportation there is a case for deriving hydrogen from the onboard reforming of an alternative fuel. This would however seriously limit the flexibility of the fuel source. For this reason a better approach would be the storage of hydrogen directly onboard as demonstrated with the hypercar concept.

Finally, the public safety perceptions of hydrogen fuel, and the absence of a history of widespread use of fuel cells are other barriers.

As fuel cell application increases and improved fuel storage methods and handling is developed, it is expected that the costs associated with fuel cell systems will fall dramatically in the future.

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