Fuel Cells Types and Characterisation

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Abstract: Fuel cell variants have been studied. The distinguishing features for the types include the electrolyte, the catalyst and the operating temperature range. Unlike alkaline, phosphoric acid and polymer electrolyte membrane fuel cells, the molten carbonate and solid oxide fuel cells can operate on a variety of fuels without suffering from carbon dioxide poisoning. In particular the solid oxide fuel cell is more tolerant to sulphur than any other fuel cell. The alkaline fuel cell is among the earliest and has been employed to produce power and water in spacecrafts. The Direct Ethanol and the Direct Methanol fuel cells are variants of the Polymer Electrolyte Membrane. Whereas hydrogen is used as fuel in the polymer electrolyte membrane, ethanol and methanol are respectively the fuels for the direct ethanol and direct methanol fuel cells. This group of fuel cells are suitable for portable applications. The use of direct ethanol and methanol fuel cells for transport will not only benefit from existing storage infrastructure but also overcome the problem associated with hydrogen handling. The regenerative fuel cell runs in the reverse mode by using electricity and one substance to produce another substance.

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1. Introduction

The need for less dependence on fast depleting fossil fuel sources, instability in most regions of sources of crude oil, geopolitical independence and the combating of global warming have all combined to focus attention on reducing our individual carbon footprint. The cumulative result of all these is to bring to the forefront the search for sustainable and environmentally friendly energy resources. Alternative energy resource options include, among others solar, wind, geothermal and biomass. The raw biomass is available from many sources and in many forms as finished product. Jatropha, farm and municipal wastes, corn, palm oil, sugarcane etc are just but a few of the available biomass feedstock. However, the sourcing of biofuel feedstock from food crop is currently a highly debatable topic. The biofuels resulting from the feedstock include biodiesel, ethanol and methanol. These fuels are currently used as blends with petroleum fuels and burnt in power stations to generate electricity. A further area of application as part of the hydrogen economy is in fuel cells where they could be reformed to provide hydrogen or used "neat". The fuel cell is an **electrochemical energy conversion device**. A fuel cell converts the chemicals hydrogen and oxygen into water and in the process produces electricity. The fuel cells may be classified based on the type of electrolyte used. This classification determines the kind of chemical reactions that take place in the cell, the kind of catalysts required, the temperature range in which the cell operates, the fuel required, and other factors. These characteristics, in turn, affect the applications for which these cells are found most suitable. There are several types of fuel cells currently under development, each with its own advantages, limitations, and potential applications. This study is interested in the various forms of fuel cell and the potential contributions they make in the search for sustainable non polluting energy resources

2.1 Molten Carbonate Fuel Cell

The development of molten carbonate fuel cell (MCFC) is on a similar line as the solid oxide fuel cell (SOFC) units and much of the initial work undertaken on MCFC technology was influenced by the research of Baur and Preis who, in the 1930s, manufactured and tested a series of ceramic materials for use as an electrolyte in the SOFC system (Crawley, 2007A). Molten carbonate fuel cells (MCFC) are high-temperature fuel cells that use an electrolyte consisting of a molten carbonate salt mixture suspended in a porous chemically inert ceramic lithium. Salts commonly used include lithium carbonate, potassium carbonate and sodium carbonate. Typically, MCFC units reach operating efficiency of around 65% and this high efficiency is another reason they offer significant cost reductions over phosphoric acid fuel cells (PAFCs). If co-generation is employed, the operation efficiency of the molten carbonate fuel cells can be increased to 80%, a value considerably higher than the 37%–42% efficiencies of a phosphoric acid fuel cell plant. Upon heating, the salts melt and generate carbonate (carbon trioxide) ions. These ions flow away from the cathode to the anode where they combine with hydrogen to produce water, carbon dioxide and electron. The electrons travel through an external circuit to generate electricity.

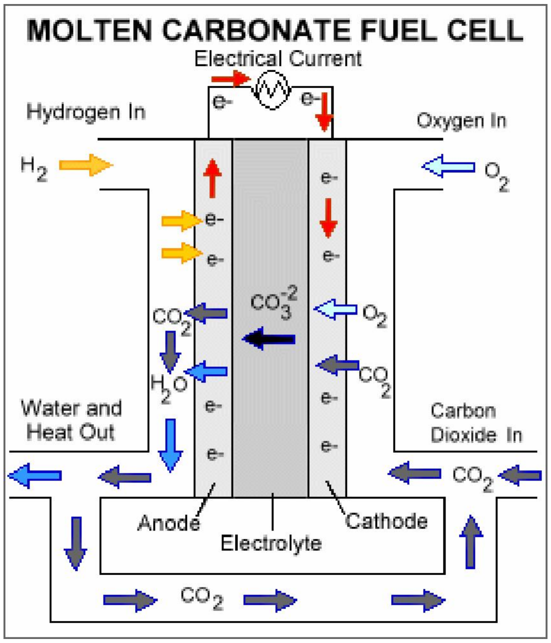

Figure 1. Schematic of a molten carbonate fuel cell (EERE, DoE)

There are several advantages associated with the MCFC system. Firstly, the high temperature of operation dramatically improves reaction kinetics and removes the need for a noble metal catalyst. The MCFC systems unlike alkaline, phosphoric acid and polymer electrolyte membrane fuel cells, can operate on a variety of different fuels and do not require an external reformer to convert more energy-dense fuels to hydrogen (EERE, 2011). The high operating temperatures, 650oC and above make it possible to convert these fuels to hydrogen within the fuel cell itself by a process called internal reforming which can lead to cost reduction. Molten carbonate fuel cells are not prone to carbon monoxide or carbon dioxide "poisoning" —they can even use the oxides of carbon as fuel—making them more attractive for fuelling with gases made from coal. If the molten carbonate fuel cell can be made resistant to impurities such as sulphur and particulates, then there is the possibility that it can sustain internal reforming of coal to provide fuel for the fuel cell. The main issue with current MCFC technology is durability. The high temperatures at which these cells operate and the corrosive electrolyte used accelerate component breakdown and corrosion, decreasing cell life. Currently, there are studies exploring corrosion-resistant materials for components as well as fuel cell designs that increase cell life without decreasing performance.

MCFC systems are generally thought to be best suited for providing stationary power and the generation of heat and electricity for industrial applications.

2.2 Solid Oxide Fuel Cell

Solid oxide fuel cells (SOFCs) use a hard, non-porous ceramic compound as the electrolyte and operate at very high temperatures of about 1000°C. The SOFC in construction consists of the anode and the cathode separated by solid ceramic electrolyte such as zirconium oxide stabilised with yttrium oxide. Because the electrolyte is a solid, the cells may not be constructed in the plate-like configuration typical of other fuel cell types. There are two basic builds of the SOFC unit referred to as the planar and tubular design. In the planer design the components are assembled in flat stacks and the air and hydrogen flow though the unit via channels built into the anode and cathode. In the tubular design, air is supplied to the inside of an extended solid oxide tube (which is sealed at one end) whilst fuel flows round the outside of the tube. The tube itself forms the cathode and the cell components are constructed in layers around the tube. In operation, oxygen (in the form of air) is supplied at the cathode. The ceramic electrolyte conducts oxygen ions from the cathode to the anode whilst electrons are pushed round an external circuit to produce electricity. At the anode, the oxygen ions combine with hydrogen to produce water (Crawley, Jan 2007B).

High-temperature operation removes the need for precious-metal catalyst, thereby reducing cost. It also allows SOFCs to reform fuels such as natural gas internally, which enables the use of a variety of fuels and reduces the cost associated with adding a reformer to the system. SOFCs are expected to be around 50%–60% efficient at converting fuel to electricity but in applications designed to capture and utilize the system's waste heat (co-generation), overall efficiencies could top 80%–85%.

High-temperature operation has disadvantages. It results in a slow startup and requires significant thermal shielding to retain heat and protect personnel, which may be acceptable for utility applications but not for transportation and small portable applications. The high operating temperatures also place stringent durability requirements on materials. The development of low-cost materials with high durability at cell operating temperatures is the key technical challenge facing this technology.

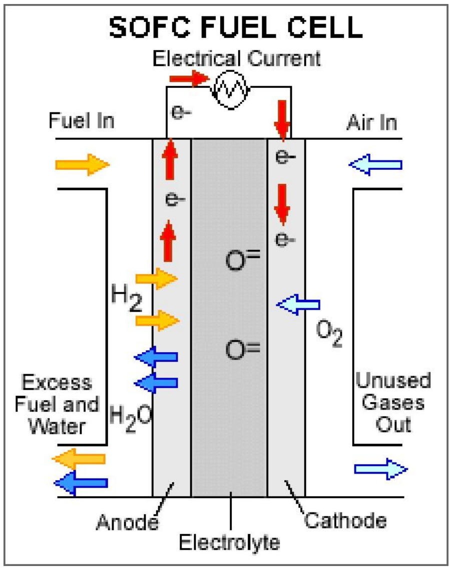

Figure 2, Schematic of Solid Oxide Fuel Cell (EERE, DoE)

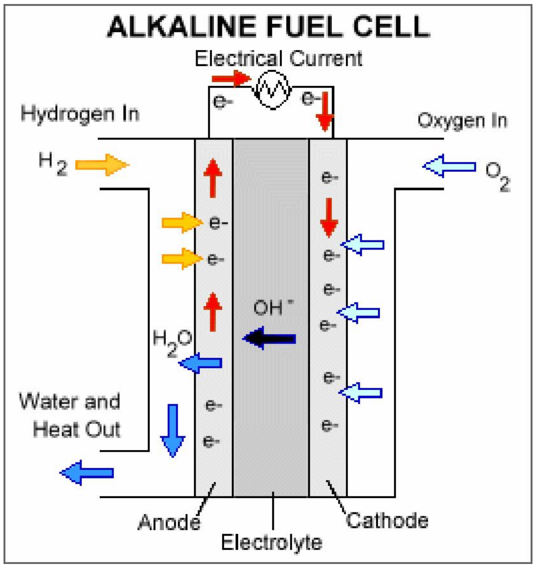

Figure 3. Schematic of Alkaline Fuel Cell (EERE, DoE)

SOFCs are also the most sulphur-resistant fuel cell type; they can tolerate several orders of magnitude of sulphur than other cell types. In addition, they are not poisoned by carbon monoxide (CO), which can even be used as fuel. This property allows SOFCs to use gases made from coal (EERE, 2011).

The development of low temperature SOFCs is being explored for operation at or below 800°C potentially with fewer durability issues and reduced cost. Lower-temperature SOFCs produce less electric power, however, and stack materials that will function in this lower temperature range have not been identified.

There are three main areas where the SOFC systems are used including large stationary applications over 10 kW and small stationary, power generation of under 10 kW and transport as well as portable application for example uninterruptable power supply (UPS).

2.3 Alkaline Fuel Cell

The Alkaline Fuel Cell (AFC) was developed in the 1930s by F.T. Bacon and is one of the oldest fuel cells developed and as well the first deployed widely in the U.S. space program to produce electric energy and water on-board spacecrafts (Crawley 2006B). It consists of two electrodes which are separated by a porous matrix saturated with an aqueous alkaline solution, such as potassium hydroxide (KOH). The fuel cell can use a variety of non-precious metals as a catalyst at the anode and cathode. Nickel is the most commonly used catalyst in AFC units. The Aqueous alkaline solutions do not reject carbon dioxide (CO_2) so the fuel cell can become "poisoned" through the conversion of KOH to potassium carbonate (K_2CO_3). Because of this, alkaline fuel cells typically operate on pure oxygen, or at least purified air and would incorporate a 'scrubber' into the design to clean out as much of the carbon dioxide as is possible. There is an ongoing debate as to whether the poisoning is permanent or reversible. The main mechanisms of poisoning are blocking of the pores in the cathode with K_2CO_3, which is not reversible, and reduction in the ionic conductivity of the electrolyte, which may be reversible by returning the KOH to its original concentration. An alternate method involves simply replacing the KOH which returns the cell back to its original output.

The fuel cell produces power through a redox reaction between hydrogen and oxygen. At the anode, hydrogen is oxidized according to the reaction:

$H2 + 2OH = 2H_2O + 2e-$

producing water and releasing two electrons. The electrons flow through an external circuit and return to the cathode, reducing oxygen in the reaction:

$O_2 + 2H_2O + 4e- = 4OH$

and producing hydroxide ions. The net reaction consumes one oxygen atom and two hydrogen atoms in the production of one water molecule. Electricity and heat are formed as by-products of this reaction.

$2H_2 + O_2 = 2H_2O$

High-temperature AFCs operate at temperatures between 100°C and 250°C. However, newer AFC designs operate at lower temperatures of roughly 23°C to 70°C (EERE, 2011). AFCs' high performance is due to the rate at which chemical reactions take place in the cell. They have also demonstrated efficiencies near 60% in space applications.

The disadvantage of this fuel cell type is the ease by which it is poisoned by carbon dioxide (CO_2) hence the need to purify both the hydrogen and oxygen used in the cell. This purification process is costly. Susceptibility to poisoning also affects the cell's lifetime (the amount of time before it must be replaced), further adding to cost.

Cost is less of a factor for remote locations, such as space or under the sea. However, to effectively compete in most mainstream commercial markets, these fuel cells will have to become more cost-effective. AFC stacks have been shown to maintain sufficiently stable operation for more than 8,000 operating hours orders of magnitude less than the 40000 hours needed for commercial viability. This obstacle is possibly the most significant in commercializing this fuel cell technology. AFCs can produce up to 20kW of electric power. The AFC is predominantly used in niche transportation applications, powering forklift trucks, boats and submarines. It is still used in space applications and NASA continues to operate several AFC units.

2.4 Proton Exchange Membrane (Polymer Electrolyte Membrane)

The proton exchange membrane (PEM) fuel cell, first developed by the General Electric in the early 1960's, uses a thin, permeable polymeric membrane as the electrolyte and porous carbon electrodes containing a platinum catalyst. It needs only hydrogen, oxygen from the air, and water to operate and does not require corrosive fluids like some other fuel cells (Crawley, 2006A). It is typically fuelled with pure hydrogen supplied from storage tanks or on-board reformers. The membrane is very small and light and in order to catalyse the reaction, platinum catalyst is used on either side of the membrane. Within the PEM fuel cell unit, hydrogen molecules at the anode split into protons and electrons. The protons pass across the polymeric membrane to the cathode while the electrons are pushed round an external circuit to produce electricity. Oxygen (in the form of air) is supplied to the cathode and this combines with the hydrogen ions to produce water. The relatively low temperature of operation (about 80°C) allows for the system to start quickly (less warm-up time) and results in less wear on components, resulting in better durability (EERE, 2011).

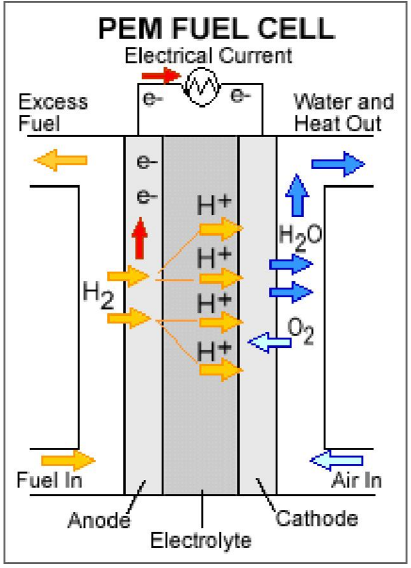

Figure 4. Schematic of Proton Exchange Membrane (EERE, DoE)

At the anode, hydrogen is catalytically split into protons and electrons in an oxidation half cell reaction thus:

$H_2 = 2H + \quad + \ 2e-$

At the cathode, oxygen reacts with the hydrogen protons and electrons to form water in a reduction half cell reaction:

$1/2O_2 + 2H^+ \ \ 2e^- = \ \ H2O + E0 \quad 1.229V$

The overall reaction can thus be represented as:

$H_2 + 1/2O_2 = H_2O \qquad E=1.229V$

Platinum as the catalyst is not very good at splitting the oxygen at the cathode. Again, the platinum catalyst is also extremely sensitive to CO poisoning, making it necessary to employ an additional reactor to reduce CO in the fuel gas if the hydrogen is derived from an alcohol or hydrocarbon fuel. This also adds to the cost. Developers are currently exploring platinum/ruthenium catalysts that are more resistant to CO. Another promising catalyst that uses far less expensive materials (iron, nitrogen, and carbon) has long been known to promote the necessary reactions, but at rates that are far too slow to be practical. However, researchers at the Institut National de la Recherche Scientifique (INRS) in Quebec have reported a dramatically increased performance of this type of iron-based catalyst by a factor 35 times better than the best nonprecious metal catalyst and this is approaching the Department of Energy goal, 130 A/cm^3 for fuel-cell-catalyst (EERE, 2007A). This result also matches the performance of typical platinum catalysts. The only problem at the moment is its durability because after only 100 hours of testing the reaction rate dropped to half. Another significant source of losses is the resistance of the membrane to proton flow, which is minimized by making it as thin as possible, on the order of 50 µm.

The PEMFC is a prime candidate for vehicle and other mobile applications of all sizes down to mobile phones, because of its compactness. However, the water management is crucial to performance: too much water will flood the membrane, too little will dry it; in both cases, power output will drop. Water management is a very difficult subject in PEM systems, primarily because water in the membrane is attracted toward the cathode of the cell through polarization. A variety of solutions do exist including the integration of electro-osmotic pump.

Platinum is expensive to be used as a catalyst. The U.S. Department of Energy estimates that platinum-based catalysts will need to use roughly four times less platinum than is used in current PEM fuel cell designs in order to represent a realistic alternative to internal combustion engine (EERE, 2007B) . The total surface area of catalyst available to participate per unit volume of platinum may be increased by reducing the particle size or by the use of high index facets of platinum nonoparticles to provide greater density of reactive sites for oxygen reduction (Ding et al, 2007).

PEM fuel cells are used primarily in transport applications and some stationary applications. Due to their fast startup time, low sensitivity to orientation, and favourable power-to-weight ratio, PEM fuel cells are particularly suitable for use in passenger vehicles, such as cars and buses. The PEMFC is reported to generate up to 250kW electric power. As the electrolyte is a solid rather than a liquid, the sealing of the anode and cathode gases is far easier and this in turn makes the unit

cheaper to manufacture.

A significant barrier to using these fuel cells in vehicles is hydrogen storage. Most fuel cell vehicles (FCVs) powered by pure hydrogen must store the hydrogen on-board as a compressed gas in pressurized tanks. Due to the low-energy density of hydrogen, it is difficult to store enough hydrogen on-board to allow vehicles to travel similar distance as gasoline-powered vehicles before refuelling, typically 300–400 miles. Higher-density liquid fuels, such as methanol, ethanol, natural gas, liquefied petroleum gas, and gasoline, can be used for fuel, but the vehicles must have an on-board fuel processor to reform the methanol to hydrogen. This requirement increases costs and maintenance. The reformer also releases carbon dioxide (a greenhouse gas), though less than that emitted from current gasoline-powered engines.

2.5 Direct *Ethanol* Fuel Cell

The Direct Ethanol Fuel Cell (DEFC) is designed on the same principles as the DMFC. It is not however as toxic as Methanol and ethanol is attractive as it already has established supply chain infrastructure. It is easier to work with ethanol for widespread use by consumers. Ethanol liquid is hydrogen-rich and has an energy density (8.0 kWh/kg) higher than methanol (6.1 kWh/kg). Ethanol can be sourced from various biomass through the process of fermentation. Feedstock includes renewable resources such as sugarcane, wheat, corn and straw. Bio-generated ethanol (or bio-ethanol) is thus attractive since growing crops for biofuels absorbs much of the carbon dioxide emitted to the atmosphere from fuel used to produce the biofuels, and from burning the biofuels themselves. Platinum-based catalysts are used for the oxidation of the organic molecules. CO_2 sequestration at the point of bio-fuel production is also another way to control the carbon dioxide release to the atmosphere.

The half-reactions are:

At the anode: (oxidation)

$C_2H_5OH + 3H_2O = 12H^+ + 12e^- + 2CO_2$

At the Cathode: (reduction)

$3O_2 + 12H^+ + 12e- = 6H_2O$

The overall reaction :

$C_2H_5OH + 3O_2 = 3H_2O + 2CO_2$

On 13 May 2007 A team from the University of Applied Sciences in Offenburg during Shell's Eco-marathon in France successfully presented the first DEFC powered vehicle The car "Schluckspecht" successfully completed a test drive on the Nogaro Circuit attaining an output voltage range between 20 and 45 V (Schluckspecht, 2011).

Various prototypes of Direct Ethanol Fuel Cell Stack mobile phone chargers featuring voltages from 2V to 7V and powers from 800mW to 2W have been built and tested (FCTec, 2011), (Amrani and Richard, 2006).

2.6 Direct Methanol Fuel Cell

There are two types of fuel cell that use methanol and they are the Indirect Methanol Fuel Cell (IMFC) usually referred to as steam Reformed Methanol Fuel Cell (RMFC) and the direct Methanol Fuel Cell (DMFC). For the Indirect Methanol Fuel Cell, the methanol is steam reformed before being fed into the fuel cell. . Methanol unlike other hydrocarbon fuels is capable of being steam reformed into hydrogen at low temperatures. A typical RMFC consists of the fuel processing section, the fuel cartridge, the fuel cell and balance of the plant (BoP).

Direct-methanol fuel cell, DMFC is a fuel cell in which “neat” methanol is used as the fuel. Although efficiency is quite low this system benefits from easy of transport, energy dense characteristics, reasonable stability at all environmental conditions and the absence of complex steam reforming component. The DMFC is aimed at processes, for example, road transport where portability is important Methanol has to be fed in weak solution in order to reduce the quantity diffusing to the cathode (Cross-over) and reacting with the air resulting in reduced cell voltage. The DMFC relies upon the oxidation of methanol on a catalyst layer to form carbon dioxide. Water is consumed at the anode and is produced at the cathode. Protons (H^+) are transported across the proton exchange membrane - often made from Nafion - to the cathode where they react with oxygen to produce water. Electrons are transported through an external circuit from anode to cathode, providing power to connected devices. The half-reaction is as follows:

Oxidation at the anode:

$CH_3OH + H_2O \rightarrow 6H^+ + 6e^- + CO_2$

Reduction at the cathode:

$3/2O_2 + 6H^+ + 6e^- \rightarrow 3H_2O$

The overall, redox reaction:

$CH_3OH + 3/2O_2 \rightarrow 2H_2O + CO_2$

The oxidation half reaction at the anode involves the adsorption of methanol and water on platinum and ruthenium particles as catalyst followed by the release of protons and formation of CO_2.

Direct methanol fuel cells (DMFCs) employ a polymer membrane as an electrolyte.

The system is a variant of the polymer electrolyte membrane (PEM) cell however, the catalyst on the DMFC anode draws hydrogen from liquid methanol. This action eliminates the need for a fuel reformer and allows pure methanol to be used as a fuel.

This novel fuel cell technology uses liquid methanol as a fuel to produce electric energy, and does not require any fuel processing. Pure water and carbon dioxide are the only byproducts of the fuel cell, and no pollutants are emitted. Direct Methanol Fuel Cells offer several advantages over other current fuel cell systems, especially with regard to simplicity of design and higher energy density. Current systems rely on hydrogen gas, a substance that is more difficult to transport and store.

The operating temperature for DMFCs is in the range of 60-130°C but is typically around 120°C, producing an efficiency of about 40%. DMFC units are best suited to portable applications and have been used in a wide variety of portable electronic products such as mobile phones and laptop computers. (Crawley, 2007C) has reported that Antig Technology of Taiwan in 2007produced a 16W battery charger for use on MP3s, mobile phone and GPS receivers. Crawley further reported that in 2000, Ballard and Daimler Chrysler introduced a DMFC powered light duty vehicle which presumably is a one off since no follow on DMFC passenger cars have been released.

Due to the low temperature conversion of methanol to hydrogen and carbon dioxide the DMFC system requires a noble metal catalyst. The cost associated with this catalyst is outweighed by the ability of the unit to function without a reforming unit. By using liquid methanol as a fuel some of the storage problems associated with hydrogen are eliminated. In addition, liquid methanol is often considered to be easier to transport and supply to the public using current infrastructure. DMFC operations are more efficient at high temperatures and pressures, but these conditions end up causing so many losses in the complete system that the advantage is lost; therefore, atmospheric-pressure configurations are preferred nowadays (Dohle et al, 2002). Approval for the carriage of DMFC cartridges aboard aircrafts by various international organisations and the US Department of Transportation has variously been reported (Marholl 2010, FuelCellToday 2007, and DoT, 2008)

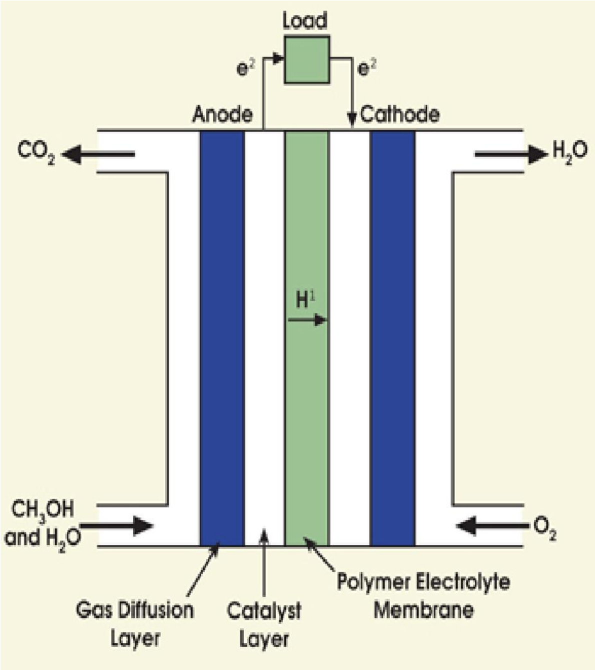

Figure 5. Schematic of a direct methanol fuel cell (EERE, DoE)

2.7 Phosphoric Acid Fuel Cell

Phosphoric acid fuel cell is among the first generation of fuel cells and the first in use commercially. It consists of a Teflon-bonded silicon carbide matrix containing liquid phosphoric acid electrolyte with porous carbon electrodes and platinum catalyst.

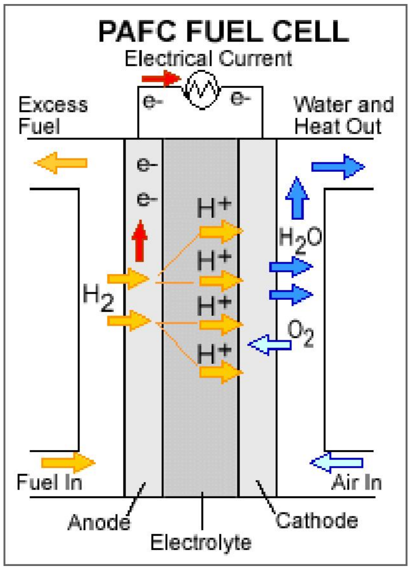

Figure 6. Phosphoric Acid Fuel Cell (EERE, DoE)

This type of fuel cell is typically used for stationary power generation, but some PAFCs have been used to power large vehicles such as city buses.

PAFCs are more tolerant to impurities in fossil fuels that have been reformed into hydrogen than PEM cells. In operation, PAFC can attain efficiency of 85% in co-generation and 37% to 42% in electricity generation alone. On weight to weight basis PAFCs are also less powerful than other fuel cells and therefore for a given capacity are larger and heavier that other fuel cells. They are also expensive because of the platinum catalyst.

2.8 Regenerative fuel cell

A Regenerative Fuel Cell (RFC) uses electricity and one chemical while running in the reverse mode to produce another chemical. It could also be referred to as reverse fuel cell (RFC). It is possible to reverse the process of any fuel cell (Ecosoul, 2011). However, it is usual to optimise processes in one mode operation in the reverse mode the system may not function optimally and very efficiently unless they are purpose-built to do so, for example high-pressure electrolysers regenerative fuel cells (Juelich, 2001), solid-oxide electrolyser cells and unitized regenerative fuel cells (Burke, 2003). A hydrogen fueled proton-exchange membrane fuel cell, for example, uses hydrogen gas (H_2) and oxygen (O_2) to produce electricity and water (H_2O); a regenerative hydrogen fuel cell uses electricity and water to produce hydrogen and oxygen (UCI 2011), (Bents and Scullin 2011).

The following reactions describe the chemical process in the hydrogen generation mode:

At cathode: $H_2O + 2e^- \rightarrow H_2 + O^{2-}$
At anode: $O^{2-} \rightarrow 1/2O_2 + 2e^-$
Overall: $H_2O \rightarrow 1/2O_2 + H_2$

One example of RFC is solid oxide regenerative fuel cell which operates at high temperatures with high fuel to electricity conversion ratios. The solid oxide regenerative fuel cell is a good candidate for high temperature electrolysis (Laguna-Barcero et al). Less electricity is required for electrolysis process in SORFC.

Table 1 below is a summary of the fuel cell types and their main characteristics.

Type & Electrolyte	**Temp oC & Size**	**Efficiency/ Applicatn**	**Advantge/ Disadvtge**
Polymer Electrolyte Mmbrane (PEM)/ Perfluoro Sulphoric acid	50-100oC Typicall 80 oC/ 1kW – 100kW	Trasnport 60% Stationary 35%/ Backup Power, Portable Power Distributed generatn Transportation Speciality Vehicles	Solid electrolyte reduces corrosion & electrolyte management problems, Low temperature, Quick startup/ Exensive catalyst, Sensitive to impurities, Low temp waste heat
Alkaline Fuel Cell (AFC)/ Aqueous solution of potassium hydroxide soaked in a matrix	90-100 oC/ 10 – 100kW	60%/ Military & space	Cathode reaction faster in alkaline electrolyte, leads to high performance , low cost components/ Sensitive to CO2 in fuel and air, electrolyte management
Phosphoric Acid Fuel Cell (PAFC)/ Phosphoric acid soaked in a matrix	150-200oC/ 400kW 100kw module	40%/ Distributed generation	High temperature enables CHP, increased tolerance to fuel impurities/ Pt catalyst, long startup time, low current & power

Molten Carbonate Fuel Cell (MCFC)/ Solution of lithium, sodium and/or potassium carbonates, soaked in a matrix	600 -700°C/ 300kW-3mW 300kW module	45-50%/ Electric utility, distributed generation	High efficiency, fuel flexibility, can use a variety of catalysts, suitable for CHP / High temperature corrosion and breakdown of cell components, long startup time, low power density
Solid Oxide Fuel Cell (SOFC)/ Yttria stabilised zirconia	700-1000°C / 1kW-2mW	60%/ Auxiliary power, Electric utility, Distributed generation	High efficiency, Fuel flexibility, can use a variety of catalysts, solid electrolyte, suitable for CHP & CHHP, hybrid/GT cycle/ High temperature corrosion & breakdown of cell components, high temperature operation requires long startup time and limit

Table 1. Summary of Fuel Cell Types and Features (Source EERE, Feb 2011).

3. Conclusion:

1. If the molten carbonate fuel cell can be made resistant to impurities such as sulphur, it may be capable of internal reforming of coal to hydrogen since it is not affected by carbon dioxide poisoning
2. The high operating temperature of the solid oxide fuel cell removes the need for expensive precious metal catalyst. In cogeneration configuration, the SOFC can attain up to 85% efficiency.
3. The purification of both oxygen and hydrogen may be necessary in alkaline fuel cell in order to reduce CO_2 poisoning.
4. The direct methanol and direct ethanol fuel cells are a derivative of polymer electrolyte membrane. . The only distinguishing feature of the three is the fuel used.
5. A summary of the fuel cell types and their main characteristics have been given a tabular form.

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