Fuel cells - an introduction

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Fuel cells are electrical batteries, which are characterised by the active materials on the electrodes being continuously replenished. Just like in other batteries the chemical process is divided up into the reducing part (cathode), which is supplied with air or pure oxygen, and the oxidising part (anode), where the fuel is hydrogen. The electrodes are separated by an ion conducting electrolyte, which is usually a membrane. A single fuel cell usually yields 0.5 -1 Volt, and hence a battery usually consists of a stack of fuel cells, where one cell's cathode is connected to the next cell's anode, and so forth. The hydrogen may be produced directly from methanol, natural gas or other simple organic compounds in a reformer connected to the battery on site. In some types of fuel cells reforming may take place directly on the surface of the electrode.

Which types of fuel cells are available?

The five most important types of fuel cells, in order of increasing operational temperature range, are:

Proton Exchange Membrane Fuel Cell (PEMFC)

Proton Exchange Membrane Fuel Cell (PEMFC), also called **PEFC** (Polymer Electrolyte Fuel cell) or **SPFC** (Solid polymer Fuel Cell), uses a solid proton conducting membrane as electrolyte and the electrode materials are normally made from carbon covered with a platinum catalyst. The reaction equations are:

Anode: $2H_2 \text{-->} 4\,H^+ + 4\,e^-$
Cathode: $O_2 + 4\,H^+ + 4\,e^- \text{-->} 2\,H_2O$
Total reaction: $2\,H_2 + O_2 \text{-->} 2\,H_2O$

The hydrogen ions pass through the membrane and the electrodes pass through the outer circuit.

Most available membranes are variations of perfluorosulphonic acid, e.g. Nafion®, which allows an operational temperature up to 120 °C. The membrane requires humidification of the gas and the control of this and the heat transportation are critical to the optimal function of this type of fuel cell. The need for a high water content practically limits the temperature of operation to 80ºC. An additional problem is that at lower temperatures the reformation gas requires purification for carbon monoxide (CO), which poisons the catalyst.

Danish Power Systems (DPS) has developed a new type of PEMFC with a membrane, which can function at temperatures up to 200 °C. At this temperature the fuel cell is able to operate at carbon monoxide concentrations of up to at least 3%. No humidification of the gas is required and current densities of up to
1 Ampere/cm^2 at 0.5 Volt, i.e. 0.5 Watt/cm^2, are achieved.

The DPS version of the PEMFC may be combined with a methanol-to-hydrogen reformer, which can operate at comparable temperature. In this case the reformer can get a large part of the necessary heat directly from the fuel cell's excess heat production, and over all the total energy efficiency is enhanced.

Direct Methanol Fuel Cells (DMFC)

A fair amount of research is conducted in Direct Methanol Fuel Cells (DMFC), which are characterised by reforming the methanol directly on the anode surface through the use of a suitable catalyst (Pt-Ru /C). Normally the membrane is Nafion® and the construction similar to the PEMFC mentioned above. Fuel cells have been described which operate with a gas flow or with a liquid flow, where the methanol used is a 2 molar aqueous solution, occasionally with additives.

DMFC has a number of advantages such as a simpler construction of the system, no poisonous emissions, no need for a reformer and, for systems with a liquid flow, there is no need for the fuel evaporator and humidification devices. However, there are also a number of disadvantages: The maximum power load of the electrode (Ampere/cm^2) is lower than for PEMFC and the methanol diffuses through the membrane and reduces the capacity of the cathode. In the gas flow version it is necessary to add significant amounts of water to the anode via a humidifier. In terns of electrical efficiency, the system is not believed to be able to compete with the DPS version of a combined PEMFC and reformer.

Phosphoric Acid Fuel Cell (PAFC)

The Phosphoric Acid Fuel Cell has a separator with phosphoric acid as the electrolyte. The electrode material is carbon coated with a platinum catalyst.
The fuel has to be hydrogen and if other fuels are used then they must first be converted into hydrogen. The operative temperature range is 150-200 °C. Common for the PAFC and the PEMFC is that the electrolyte is proton conducting (hydrogen ion conducting) so that the product of the reaction is water formed at the cathode. Research into this type of fuel cell has stagnated somewhat as it is generally considered outdated. It is found in commercial versions from 50 kW to 10 MW (electrical) for emergency electricity back up and similar systems but small installations are not widely used.

The PAFC uses pure hydrogen as fuel, but can operate with some CO_2 and it tolerates CO to the same extent as the High temperature PEMFC described above

Molten Carbonate Fuel Cell (MCFC)

In Molten Carbonate Fuel Cell (MCFC) the electrolyte is molten Potassium-Lithium-Carbonate at temperatures around 650 °C. The electrodes consist of a porous nickel and nickel oxide material. The ion transfer in the electrode is in the form of carbonate ions and hence it is necessary to add CO_2 to the cathode also in cases where the fuel produces CO_2 on the anode. Commercial installations are available and used for heating in houses with blocks of apartments.

Solid Oxide Fuel Cell (SOFC)

In Solid Oxide Fuel Cell (SOFC) the electrolyte is often a Y_2O_3 doped ZrO_2. The anode is often ZrO_2-Y_2O_3-ceramics with nickel powder and the cathode is $LaMnO_3$ doped with SrO. The parts are constructed as a single ceramic unit which operates at 700-1000 °C. SOFC (and MCFC) are characterised by (using appropriate catalysts) combusting natural gas and a variety of organic compounds directly and have a high energy efficiency yield. A commercial production of this system has recently commenced in Denmark.

What about the environment?

Fuel cells primarily use hydrogen as fuel and in this case the product is pure water. For example, for journeys to the Moon a fuel cell was used for producing electricity and the water was used as drinking water. Much research is still being conducted in hydrogen technology, especially finding alternatives to the heavy steel containers for transportation and storage of hydrogen. If the hydrogen is produced from electrolysis of water in a location with excess energy from a long-lasting energy source, then the system is basically pollution free.

The hydrogen can also be produced from natural gas, an oil product, coal or e.g. from an intermediary product such as methanol. This can be done in larger installations or in a reformer directly linked to the fuel cell where the excess heat from the fuel cell is used. In some cases the reformation can take place directly on the electrode surface, especially methanol-to-hydrogen. The SOFC type allows natural gas reformation directly on the electrode surface.

If the hydrogen is produced from natural gas, an oil based product or coal then two kinds of pollution need to be considered.

1. The raw materials contain carbon and for every carbon atom one molecule of carbon dioxide (CO_2) is produced, which adds to the green house effect, irrespective of whether the fuel is burnt in a traditional power station, in a motor vehicle, or via a fuel cell. However, it may be sensible to use fuel cells because of the enhanced energy efficiency and thus a smaller amount of fuel is required to produce a fixed amount of electricity, and less CO_2 is produced.

2. Fuels can contain impurities and through the reforming process carbon monoxide (CO) is formed in trace amounts. However, the amounts of pollution, and certainly NO_x and particles which are absent are usually lower than that produced by a combustion engine. If the reforming process takes place separately from the fuel cell then the fuel cell part may be considered almost pollution free. There will be a real environmental advantage in urban areas when driving electric cars powered by hydrogen (or methanol) via fuel cells, even if the fuel is produced elsewhere with some pollution as a result.

Further information

Danish Power Systems (DPS) is a private consultancy and production firm based in Copenhagen, Denmark, mainly consisting of chemical and electrochemical engineers, and researchers associated with Danish Technical University. For further information regarding the development of domestic or industrial applications or commercial joint ventures, please contact daposy@daposy.dk.

Biography

Jens Oluf Jensen has a M.Sc. in chemical engineering from the Technical University of Denmark (DTU) and a Ph.D. in electrochemistry (1997).
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Erik Hennesø has a M.Sc. in chemical engineering from the Technical University of Denmark (DTU) and a Ph.D. in electrochemistry from DTU (1976) and 40 years of industrial and university research experience in batteries and fuel cells. He is one of the founding members of Danish Power Systems.