Fuel cells for low power applications

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Abstract

Electronic devices show an ever-increasing power demand and thus, require innovative concepts for power supply. For a wide range of power and energy capacity, membrane fuel cells are an attractive alternative to conventional batteries.

The main advantages are

- the flexibility with respect to power and capacity achievable with different devices for energy conversion and energy storage,
- the long lifetime and long service life,
- the good ecological balance,
- very low self-discharge.

Therefore, the development of fuel cell systems for portable electronic devices is an attractive, although also a challenging, goal. The fuel for a membrane fuel cell might be hydrogen from a hydride storage system or methanol/water as a liquid alternative. The main differences between the two systems are

- the much higher power density for hydrogen fuel cells,
- the higher energy density per weight for the liquid fuel,
- safety aspects and infrastructure for fuel supply for hydride materials.

For different applications, different system designs are required. High power cells are required for portable computers, low power methanol fuel cells required for mobile phones in hybrid systems with batteries and micro-fuel cells are required, e.g. for hand held PCs in the sub-Watt range. All these technologies are currently under development. Performance data and results of simulations and experimental investigations will be presented. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Fuel cells; Power applications; Diffusion layers

1. Introduction

Membrane fuel cells offer—due to their solid electrolyte—a variety of possibilities in design. The solid electrolyte is usually covered with a thin electrolyte layer forming a membrane/electrode assembly (MEA) with a thickness in the range of 20–100 μm. MEAs are flexible and can be adapted to various geometries. Onto this MEA, a layer for gas distribution and current collection is pressed. The required homogeneous pressure over the active electrode area has to be considered in the construction of small cells in the low power range. Additional limiting conditions are the removal of water or water management in general, and heat removal.

By various construction techniques, the current, the voltage and the geometric design of the fuel cell may be adapted to the requirements of the application. A high current is realised by enlarging the active area of the membrane/electrode assemblies, a high voltage by series connection of a certain number of cells and the exterior dimensions are determined by the arrangement of series-connected cells in a stack [2] or in the plane of a membrane (banded structure membrane [1]). Several different possible concepts are shown in Fig. 1.

For portable applications, the boundary conditions are

- operation at ambient conditions (pressure, temperature),
- air breathing cathodes,
- as few peripheral devices as possible (pumps, valves, fans, etc.).

At the same time, a high power density and a reliable operation in the hands of the customer is required. Thus, the

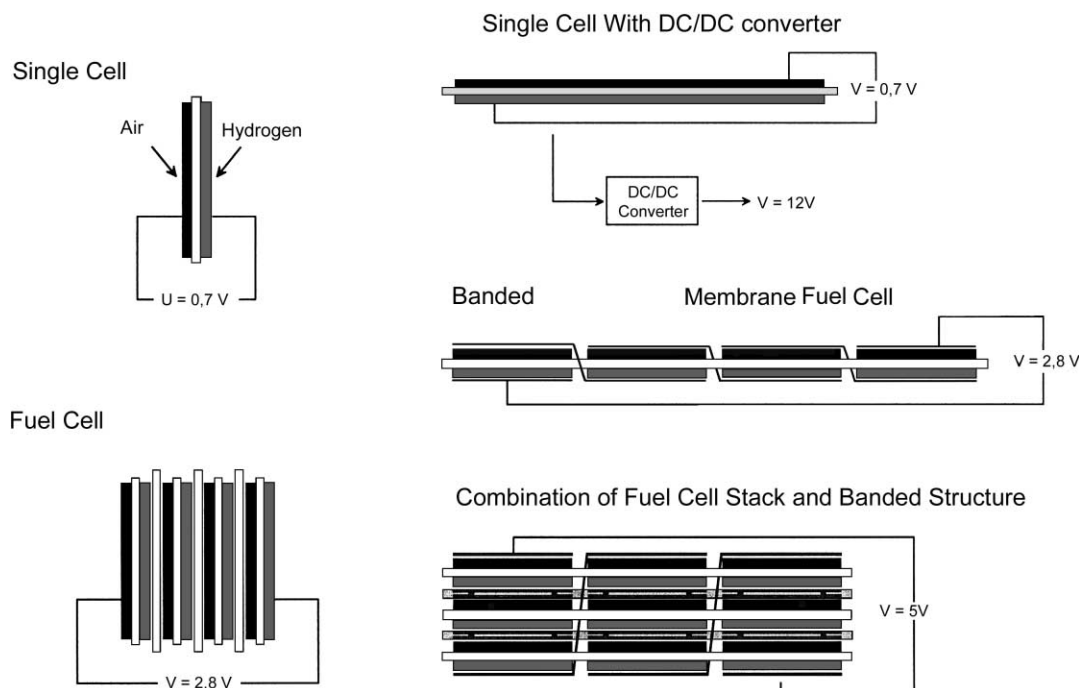* Corresponding author. Tel.: +49-761-4588-194;
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Fig. 1. Construction principles of membrane fuel cells.

development of portable fuel cells as energy supply systems for electronic devices still is a challenge.

2. Components

2.1. The membrane/electrode assembly

In the past few years, rapid progress has been made with respect to the availability of commercial membranes and MEAs. Therefore, different MEAs have been investigated in the course of the development of small fuel cells:

- coating of Nafion[TM] according to a spraying or hot pressing procedure with catalyst samples of various suppliers,
- investigation of samples of PEEK-MEAs complete with diffusion layer,
- investigation of GORE[TM] select MEAs with Gore[TM]Carbel diffusion layer.

Cell construction has been improved simultaneously. But the main arguments for the selection of a MEA are that

- the realisation of a high power density at ambient conditions requires a thin and highly conductive membrane,
- water management is easier with MEAs supporting the formation of the product water at the cathode side of the cell,
- reliable start up of the cell after prolonged time of standstill (storage without use) is possible.

For example, the requirement for active water management, which means water removal during operation at high power densities, and the water storage for times without operation to keep the membrane in a sufficiently humidified state—and a simple air breathing construction of the cell, are in contradiction. Therefore, the task of micro-structuring fuel cell components to fulfil all the requirements and to adapt the cell construction to the MEA—which up to now has not been finally selected—is still going on.

The optimisation of the diffusion layer also is a task closely linked to the properties of the MEA, and the fuel and air supplies to the cell. A good electric conductivity, in combination with a sufficient amount and size of pores to guarantee the fuel and air supply to the electrode and a pore structure supporting product water removal, is needed and has been the subject of investigations by other groups [3,4].

Experiments with respect to modifying Toray[TM]Carbon papers have been carried out. The electric conductivity of the carbon paper, which has large pores as depicted in Fig. 2, can be achieved by filling a part of the pores with carbon black or a mixture of carbon black and PTFE, if hydrophobic properties are preferred.

In Table 1, the ohmic resistances of some samples are given.

The power densities attainable are closely related to the cell resistance and other effects like the hydrophobicity of the backing layer only have a minor influence on these experiments in small test cells. Fig. 3 shows the current/voltage plots of the untreated carbon paper (470 mΩ cm^2) and a carbon paper impregnated with 1.25 wt.% PTFE-emulsion (650 mΩ cm^2).
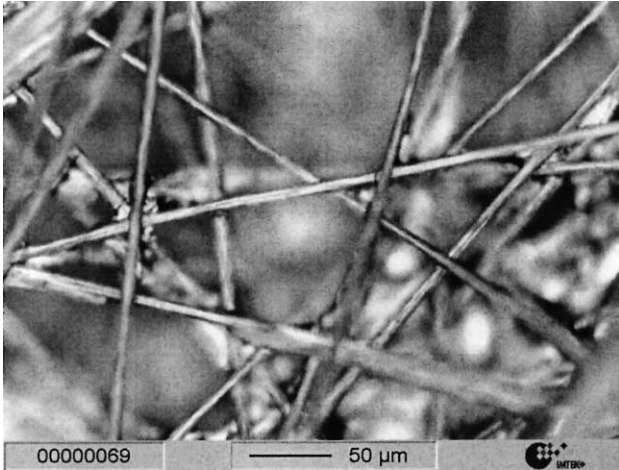
Fig. 2. Picture of a Toray™Carbon paper.

2.2. Current collectors and cell frames

In an ordinary stack, a bipolar plate serves as current collector and also contains the flow field for fuel supply to the electrode area. These bipolar plates are manufactured from graphite in combination with polymer materials [5,6] for better mechanical properties and for manufacturing reasons. These materials are the only available choice for high power density fuel cell stacks, because most metallic materials suffer from corrosion at operating temperatures as high as 80 °C.

At lower operation temperature, stainless steels and also titanium seem to be possible choices, though detailed long-term investigations will still have to be made. This is very important for cells constructed according to the banded structure principle, since, in this case no bipolar plates are required. Series connection is achieved with the aid of sheets of good electric conductors, as shown in Fig. 4.

Table 1
Ohmic resistances of the test fuel cell (3.14 cm^2 active area) with samples of different diffusion layers

| Material	Thickness (μm)	Treatment	Cell resistance (mΩ cm^2)
Carbon paper	170	–	470
Carbon paper	360	–	880
Carbon paper	170	Filled with carbon black	370
Carbon paper	170	Filled with carbon black and impregnated with PTFE-emulsion (5 wt.%)	530
Carbon paper	170	Impregnated with PTFE-emulsion (1.25 wt.%)	650
Carbon fleece	150	–	2400
Carbon fleece	150	Filled with carbon black	785
Carbon fleece	150	Impregnated with PTFE-emulsion (10 wt.%)	650
Carbon fleece	150	Filled with carbon and impregnated with PTFE-emulsion (5 wt.%)	600
Gore Carbel			380
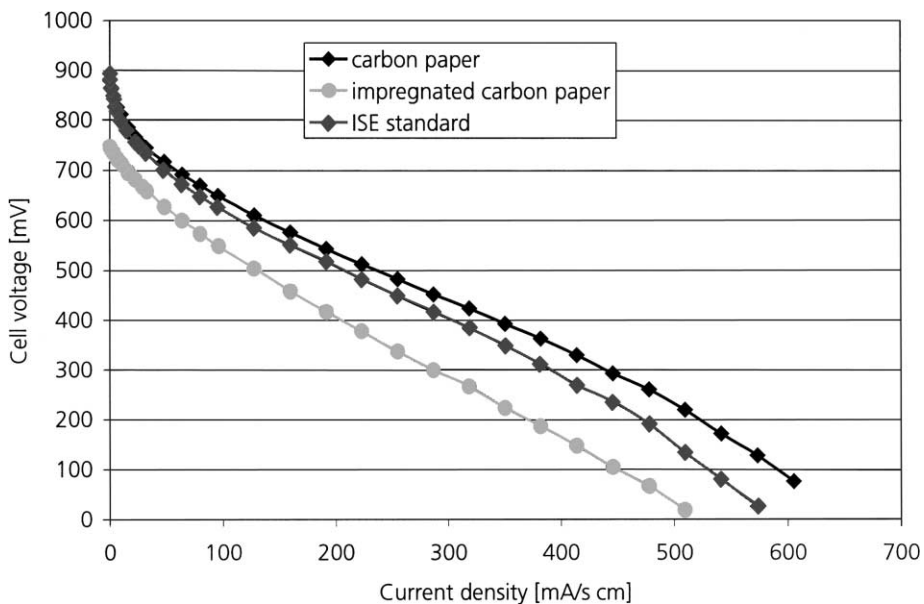
Fig. 3. Current/voltage plot of three diffusion layers with different cell resistances at ambient temperature and H$_2$/air-flow highly overstoichiometric.
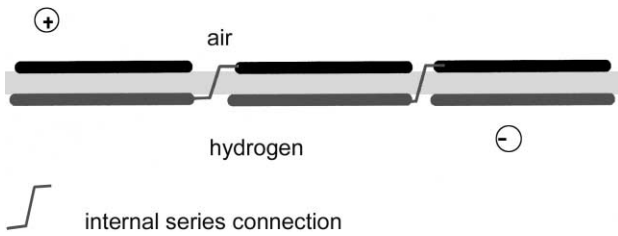
Fig. 4. A detail of a banded structure membrane.

As the current path follows the surface of the membrane and as a short circuit between adjacent cells must be excluded, the cell frame of this type of cell will be fabricated from electrically insulating polymeric materials. This feature makes cheap and simple mass production for the cell housings possible. Additionally, there is only one plane with hydrogen supply channels and a second plane for air supply for low power cells. If a higher output power is required, several of these planes can be arranged one above the other.

3. Prototypes

Several prototypes for the different concepts have been constructed and characterised. The first one was designed to power a laptop computer during a day. Consuming 15–20 W average electric power during 10 h of uninterrupted opera-

Fig. 5. Fuel cell stack with four cells and 55 W maximum power connected with a dc-converter to deliver 3.5–15 V.
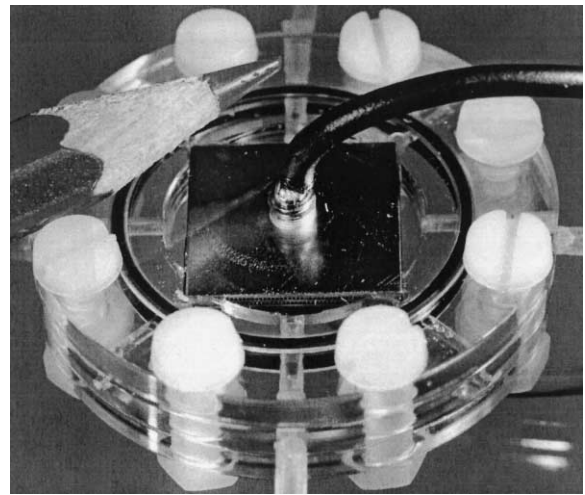

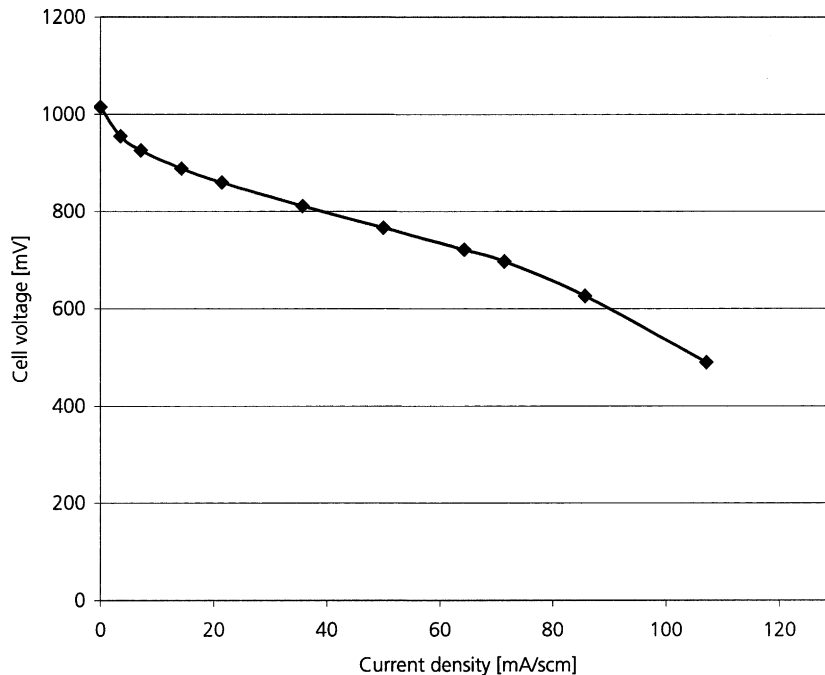Fig. 6. Five cells in a stack with a maximum power output of 250 mW.

Fig. 7. Cell performances of a single micro-structured cell with hydrogen (20 ml/min) and air (50 ml/min), ambient pressure and temperature.

tion required a hydride can with 130 l of hydrogen inside. This hydrogen can had exactly the same size as the usual battery pack of the laptop computer, which delivers power for 2–2.5 h of operation. The laboratory fuel cell stack—five banded structure membrane layers with five cells each—contributed to the volume a further 528 ml and had a weight of 1210 g. After this successful first demonstration, several other design studies of fuel cell systems have been made.

The combination of a small number of stacked cells with a dc-converter to achieve the desired output voltage is depicted in Fig. 5.

For smaller power demands, the cells can be even more compact. If only a small flow of air and hydrogen is required, the gas channels can be reduced in size. Pressure drop is the limiting factor. An example of a micro-structured fuel cell is depicted in Fig. 6.

4. Results

The main tool for characterising fuel cell stacks still is the measurement of current/voltage characteristics. In Fig. 7, the performance of one layer of the micro-structured cell stack is shown. The membrane is Nafion 117^{TM}, the catalyst coating is 2 mg/cm^2 Pt/Ru on the anode side and 2 mg/cm^2 Pt on the cathode side, and the cell was dedicated to be operated with methanol as fuel.

5. Computational simulation

In hydrogen/air fuel cells, the air electrode usually limits the power density of the cell stack. Therefore, it is interesting to know, how oxygen supply to the electrode through the air
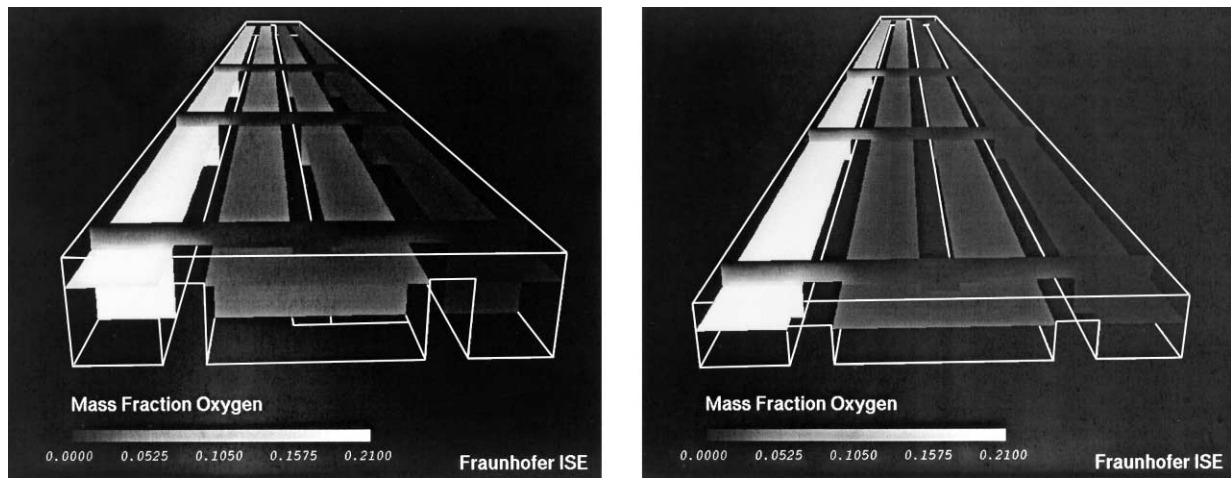

Fig. 8. Depletion of oxygen in air channels: left side, 1 mm × 1 mm channels; right side 1 mm × 0.5 mm channels. Channel length, 240 mm.
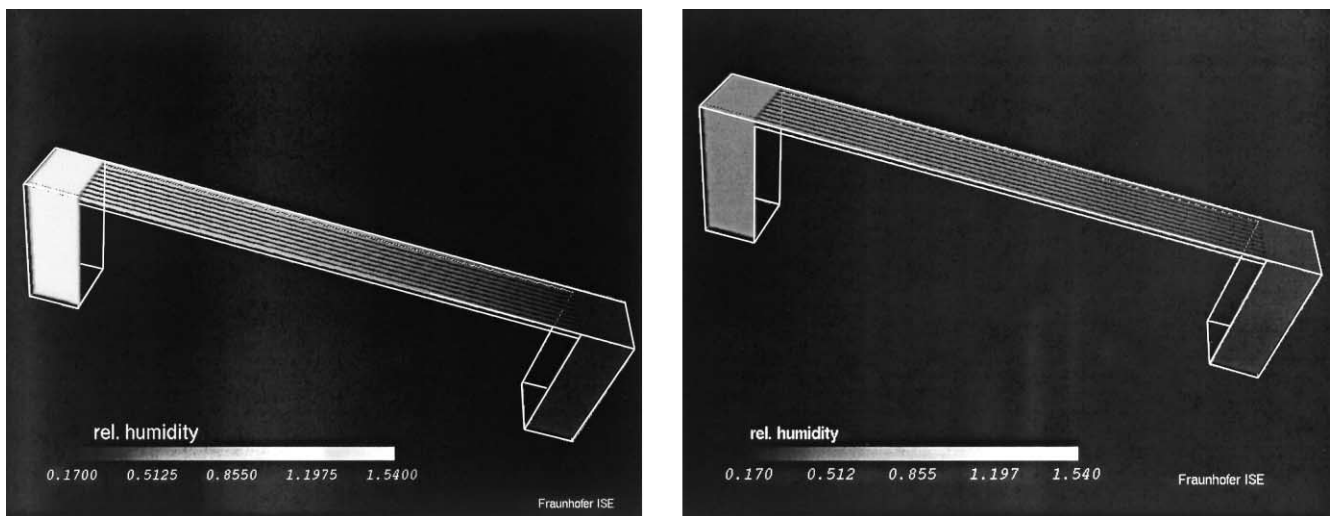

Fig. 9. Relative humidity in the air channels of a membrane fuel cell. Left side: air flow = 20 ml/min, no condensation occurs; right side: air flow = 10 ml/min, condensation is possible.

channel can be optimised. For this purpose, special sub-routines for the commercial software CFX have been implemented. The first approach takes the depletion of oxygen content in an air channel into consideration. Thus, air channels of different geometric design can be compared. A pure diffusion limitation of the current density has been assumed (Fig. 8).

The simulation has been performed under the assumption, that all oxygen molecules reaching the electrode react with protons to form water and that a constant volume flow of 200 ml/min is supplied. From these calculations, it is obvious, that smaller channels lead to a faster depletion of oxygen due to the smaller buffer volume as could be expected by a model based on a diffusion limitation (Fig. 9).

A second simulation was made with respect to the formation of water in the pathway of an air channel. Here, the basic assumptions were

- all reaction water is formed at the air electrode,
- no additional water appears due to electro-osmotic drag,
- there is no back diffusion of water through the membrane,
- isothermal conditions over the area,
- the homogenous current density is 100 mA/cm^2.

With this model, areas of potential condensation in fuel cells with or without diffusion layers can be predicted depending on the given operating conditions of the cell.

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