Evaluation of planar free-breathing polymer electrolyte membrane fuel cell design

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Abstract

A planar cell design for free-breathing fuel cell is studied. The cathode side of the cell was directly open to ambient air in a way that oxygen needed by the fuel cell reaction was provided by diffusion through the cathode side gas diffusion backing, i.e. the cell had no cathode side flow channels. The aim of the study was to demonstrate the feasibility of the cell concept by experimentally evaluating its performance with polarisation and current transient measurements. The orientation of the cell did not significantly affect the performance of the cell and signs of flooding were not observed. The maximum power density achieved in the polarisation measurements was $\sim$124 mW cm^{-2}. The current transient measurements revealed that with a small base load the cell is capable of producing momentarily current densities up to 500 mA cm^{-2}. The maximum transient power density achieved was $\sim$194 mW cm^{-2} at transient current density of 450 mA cm^{-2}. According to the results it seems that this kind of cell design is feasible for small-scale applications, such as portable computers.
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1. Introduction

Fuel cells are on their way to commercialisation especially in transportation applications. Recently, the interest to power small-scale applications, such as portable electronic devices, with fuel cells has increased.

In small-scale applications, the fuel cell should be small and have high energy density. One way to achieve these requirements can be the minimisation of number of auxiliary devices, and thus the use of passive methods to control the operation may be advantageous. From that point of view, free-breathing fuel cells, i.e. cells that take the oxygen directly from the surrounding air, may offer advantageous properties, because there is no need for auxiliary air circulation devices. Studies on free-breathing fuel cells are presented, e.g. in [1–8].

In this study, the concept of planar free-breathing polymer electrolyte membrane fuel cell (PEMFC) using a rigid gas diffusion backing on the cathode side is demonstrated. The planar cell design could be an attractive alternative for traditional free-breathing cells, in which the air is provided through straight vertical channels open to ambient air, see, e.g. [3]. In a planar cell, the gas diffusion backing is directly in contact with ambient air, and thus there is no need for

cathode side flow-field plate at all. Independently from our study, a similar kind of cell structure was recently published by Schmitz et al. [8].

The used gas diffusion backings were chosen because of their rigidity. With a rigid gas diffusion media there is less need for supporting structure such as the ridges of flow-field plates. The use of supporting structure usually reduces the effective active area of the cell because oxygen has to diffuse sideways to reach the active area beneath the supporting ridge.

Planar cell design could be advantageous especially in applications where the area of the power source is not limited, but the thickness is the critical factor. One example of such an application is portable computers.

2. Cell design and materials

The planar cell design is illustrated in Fig. 1. The cathode side of the cell is directly open to ambient air. The oxygen needed by the fuel cell reaction is transferred by diffusion through the gas diffusion backing into the cathode electrode. There is one supporting ridge on the cathode side current collector plate in order to ensure good mechanical, thermal, and electrical contact also between the central parts of the gas diffusion backing and MEA. The active area of the cell is $\sim$6 cm^2.
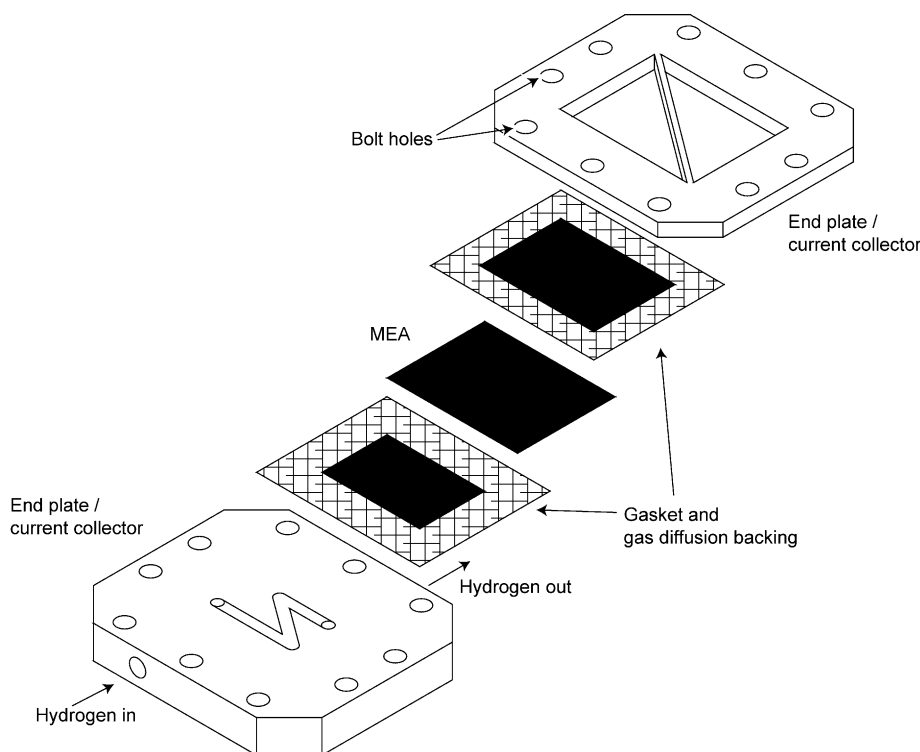
Fig. 1. Planar cell design.

The anode side end plate was made of gold-plated 316 stainless steel and it operates as a current collector and flow-field plate for hydrogen. The thickness of the plate was 10 mm, because 0.125 in. gas connectors were used in the hydrogen inlet and outlet. The thickness could be significantly reduced if the connectors were smaller or the hydrogen pipe was directly clued into the inlet of flow channel. However, the aim of this study was to demonstrate and test the cell design, and thus attempts to minimise the size were not made. The flow-field geometry was 'Z' shape, as illustrated in Fig. 1. The width of the channel was 3 mm and the depth was 1 mm.

The cathode side end plate was also made of gold-plated 316 stainless steel and it operates as the cathode side current collector. The thickness of the plate was 4 mm in order to enable the measurement of the cell temperature. The temperature was measured with a temperature probe located in a hole drilled into one side of the end plate. The thickness of this plate could also be reduced if there were no temperature measurement probe installed.

The anode side gas diffusion backing was ®SIGRACET GDL10-BB carbon paper made by SGL Technologies GmbH. The MEA was PRIMEA® MEA Series 5510 having 0.3 mg cm^{-2} platinum loading on both sides made by W.L. Gore & Associates. Two different gas diffusion backings at the cathode side were used. These were ®SIGRACET PGP 30 AA #18802 and #19802 carbon sheets (thickness 1.5 mm) made by SGL Technologies GmbH. These gas diffusion media were chosen because of their mechani-

cal rigidity which enables the minimisation of supporting structure.

The porosities of carbon sheets were calculated from the densities given by the manufacturer and they were ~78% for #18802 and 58% for #19802. According to the manufacturer, the area-specific resistance of the materials #18802 and #19802 were 110 and 90 mΩ cm^2, respectively.

3. Measurement procedure

The measurements were conducted with a GT-100 fuel cell test station made by GlobeTech Inc. A PC was used to control the test station and to record the measurement data. In most of the measurements, dry hydrogen having purity of 99.999% was fed to the anode from a pressure bottle. The minimum flow-rate of hydrogen was 7 cm^3 min^{-1} and for larger flows a current-based relation of 14 cm^3 min^{-1} A^{-1} (stoichiometry of 2) was used.

The performance of the fuel cell was characterized with polarisation and current transient measurements. A long-term measurement was also performed. The polarisation curves were measured by scanning the current with 50 mA steps and simultaneously measuring the voltage of the fuel cell. The voltage was allowed to stabilise for 60 s at each measurement point before the next current step. Before each polarisation curve measurement, the fuel cell was let to stabilise at the current density of 100 mA cm^{-2} for 15 min. Most of the polarisation measurements were conducted in

horizontal (the cathode side upwards) orientation. In order to see the effect of orientation, one polarisation curve was also measured in vertical orientation using #18802 on the cathode. In the long-term measurement, the cell was operated at a current density of 200 mA cm^{-2} for 55 h in horizontal cell orientation.

The current transient measurements were performed with #18802 at the cathode side. The flow-rate of hydrogen was set to 42 cm^3 min^{-1} (stoichiometry of 2 for 500 mA cm^{-2}) in order to eliminate the possible effects of the slowness of the flow controller to the results. The hydrogen was humidified at ambient temperature to prevent the drying of the membrane caused by the over-stoichiometric flow. The current transient measurements were performed at base levels of 50, 100 and 200 mA cm^{-2}. The current transients were recorded by increasing the current density with 50 mA cm^{-2} steps for two seconds before returning to the base level (i.e. for the 50 mA cm^{-2} base level the first step was 100 mA cm^{-2}, the second 150 mA cm^{-2}, etc.). Between current transients, the cell was operated for 60 s at the base level. The fuel cell was let to stabilise for 15 min at each base level before the current transient measurements.

Because the PGP carbon sheets are mechanically rigid but easy to machine, they could operate as a combined gas diffusion backing/flow-field plate. This was tested by blocking the original gas channel of the anode side end plate with Teflon tape and replacing the gas diffusion backing with #18802 into which a similar gas channel was machined. The cathode side gas diffusion backing in the measurement was #19802.

4. Results

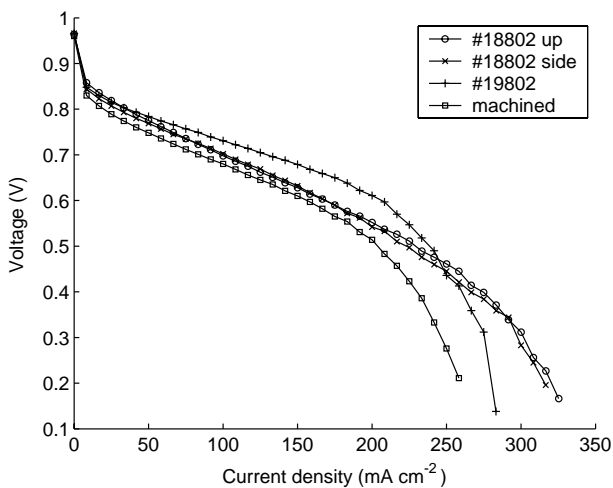The results from the polarisation measurements are presented in Fig. 2. The notation 'up' in the legend refers to the horizontal orientation, 'side' to the vertical orientation, and 'machined' to the measurement in which the machined #18802 was used at the anode side. The temperature of the cell during the polarisation measurements was 27–31 °C. There were no significant differences in the cell performance between measurements conducted in horizontal and vertical orientations. In addition, the increasing and decreasing parts of the polarisation scan overlapped, which implies that no significant flooding occurred and the conductivity of the membrane remained quite constant.

The performance differences between different materials can be explained with material properties. The slightly higher resistance of #18802 cause steeper decline to the polarisation curve in the middle region of current density range compared to #19802. It is evident that more porous #18802 has smaller mass diffusion overpotential, because the bending down of the polarisation curve occurs significantly later than with #19802. Due to smaller mass diffusion overpotential, the performance loss caused by the higher resistance of #18802 is over-compensated at current densities over 250 mA cm^{-2}.

Effects of resistance and porosity differences are both seen in the polarisation curve measured with machined #18802 at the anode side. The total resistance is high and mass diffusion overpotential caused by #19802 at the cathode begins to dominate approximately at the current density of 200 mA cm^{-2}. However, the measurement shows that the machined carbon sheet can operate as a flow-field plate.

The power densities calculated from the polarisation measurements are presented in Fig. 3. The maximum power density was obtained with #19802 and it was 124 mW cm^{-2} at the current density of 208 mA cm^{-2}. The maximum power density with #18802 was 115 mW cm^{-2} and because of smaller mass diffusion overpotential it was achieved with higher current density (250 mA cm^{-2}) than with #19802. The cell performance with machined #18802 at the maximum power point was ∼17.5% weaker than with #19802.

Fig. 2. Measured polarisation curves. Notation 'up' refers to horizontal orientation, 'side' to vertical orientation, and 'machined' to measurement in which the machined #18802 was used at the anode.
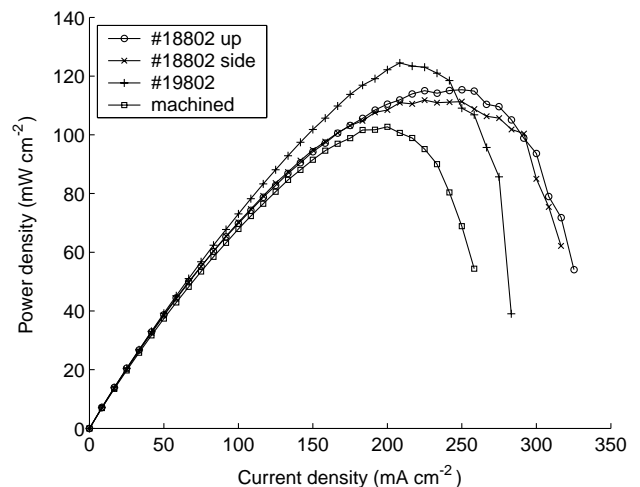

Fig. 3. Power densities calculated from the polarisation measurements.
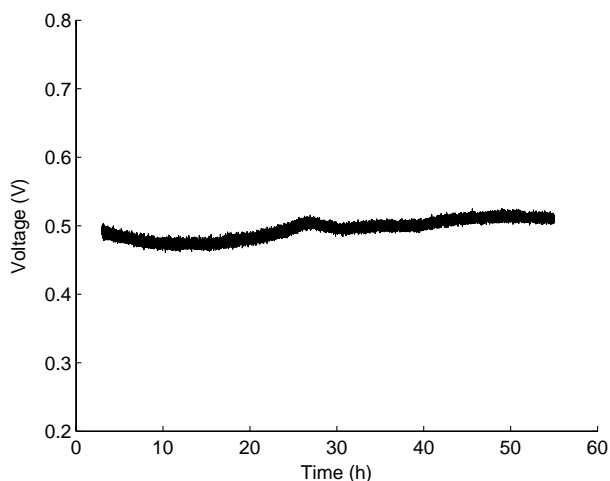
Fig. 4. Result of the long-term measurement.

The result of the long-term measurement is illustrated in Fig. 4. The temperature of the cell stabilised approximately in 2 h to 31 °C. The fuel cell operated rather stably throughout the measurement, and showed no signs of decrease in performance. In the longer time scale the fuel cell was in steady-state operation, but in five-second time scale there was a continuous voltage fluctuation of ∼0.01 V. This kind of fluctuation is typical for free-breathing fuel cells. The fluctuation can be seen as the thickness of the voltage curve in Fig. 4. The slight changes in the average cell voltage in the longer time scale may be due to possible changes in ambient conditions.

The results of current transient measurements are presented in Fig. 5. It can be seen from Fig. 5a that with the 50 mA cm^{-2} base load the fuel cell could produce short-term transient currents up to 500 mA cm^{-2}. The maximum transient power density achieved was 194 mW cm^{-2} at transient current density of 450 mA cm^{-2}. It can be seen from Figs. 5b and c that at higher base loads the response of the fuel cell to current transients was decreased. This is most probably due to the fact that with higher base load the oxygen concentration on the electrode is smaller, and thus there is not enough oxygen present for large current transients.

After the current transient, the fuel cell returned almost immediately into steady-state operation. Only after the larger current transients the voltage was somewhat higher for a
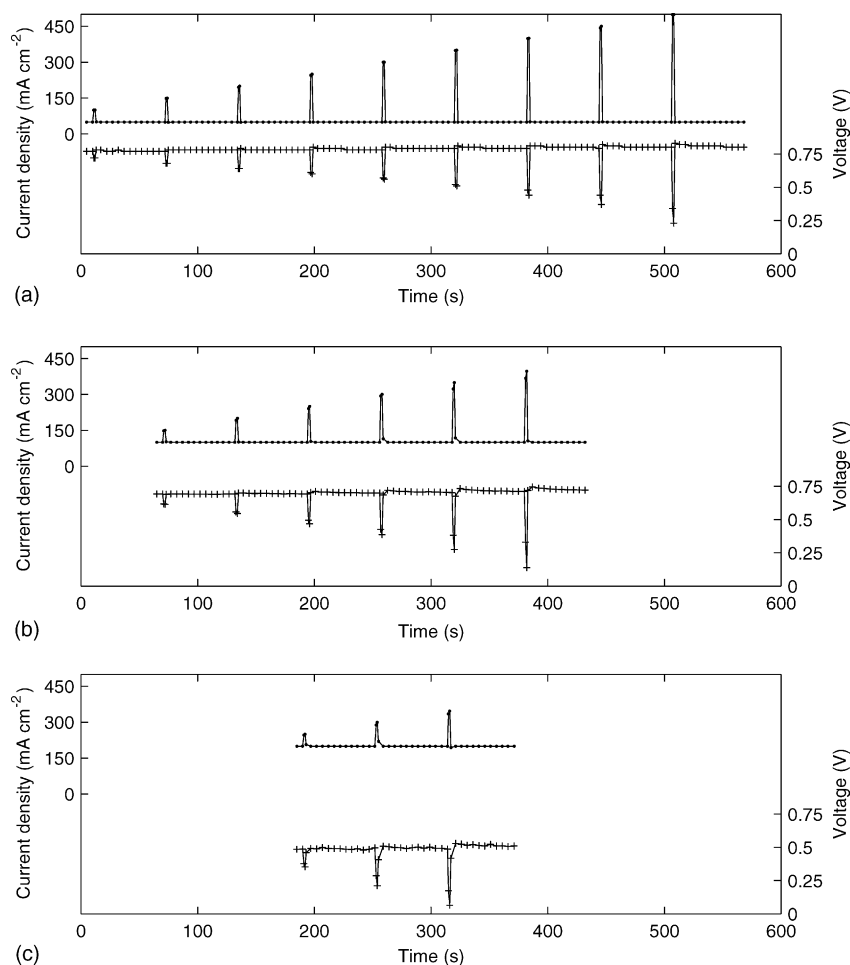

Fig. 5. Current densities (●) and voltages (+) from the current transient measurements: (a) 50 mA cm^{-2} base load, (b) 100 mA cm^{-2} base load, (c) 200 mA cm^{-2} base load.

short period. This is most probably due to increased oxygen flux caused by larger current. The oxygen flux does not decrease immediately when the current is returned to the base level, and thus there is slightly higher oxygen concentration on the electrode for a short period of time after the transient.

5. Summary and conclusions

The performance of a free-breathing PEMFC using planar design was studied. The cell had rigid gas diffusion backing on the cathode side, through which the oxygen needed by the cell reaction was transferred into the electrode by diffusion. Two different carbon sheets, both having thickness of 1.5 mm, were used as the cathode side gas diffusion backing.

The polarisation measurements showed a maximum power density of $124\, mW\, cm^{-2}$. The performance differences between different materials were explained with different electric conductivities and porosities. The long-term measurement showed a stable performance at $200\, mA\, cm^{-2}$. In short-time scale, there was a small voltage fluctuation, which is typical for free-breathing fuel cells.

Because the used gas diffusion backings were rigid but easy to machine, the capability of using these materials as a combined gas diffusion backing/flow-field plate was studied. The results showed a slightly weaker performance than with traditional thin gas diffusion backing. However, the machining of porous carbon sheet is easier and less expensive than the machining of, e.g. graphite or steel plate. Thus, the manufacturing costs of fuel cell can be brought down to some extent if a combined carbon sheet gas diffusion backing/flow-field plate is used.

The current transient measurements showed that with a small base load the fuel cell can produce short-term current transients up to $500\, mA\, cm^{-2}$. With larger base loads the fuel cell response to the transients was significantly reduced. The maximum achieved transient power density was $\sim194\, mW\, cm^{-2}$. The results imply that if the primary operating point of the fuel cell is designed for a small base load, then the fuel cell is capable of managing short-term power peaks. However, if the operating point is chosen to be the maximum power point, then virtually all power peaks have to be managed with capacitors or batteries.

There was only one support ridge in the cathode side current collector plate, and this most probably caused additional resistance because the current produced in the middle of the openings had a longer way to reach the current collector. The resistance could be decreased by increasing the number and width of the support ridges. However, this would also increase the mass diffusion overpotential because the free area for oxygen diffusion is simultaneously decreased. This phenomenon in the planar cell design is experimentally studied by Schmitz et al. [8]. Thus, in order to minimise the total losses, the number and width of the support ridges would have to be carefully optimised. The further studies will concentrate on this issue.

The presented cell design can be an attractive alternative for small-scale applications such as portable computers. The active area of the presented cell design can be easily increased. Moreover, with minor modifications a fuel cell stack with several unit cells connected in series can be made without increasing the thickness as suggested, e.g. by Heinzel et al. [9] (banded structure). If there is enough free area in the fuel cell application, the voltage and power demands can easily be fulfilled by changing the active area and number of unit cells.

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