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Published in:

Proceedings of the Fuel Cell Seminar 2006 Conference

Publication date:
2006

Document Version
Publisher's PDF, also known as Version of record

[Link to publication from Aalborg University](#)

Citation for published version (APA):

Andreasen, S. J., Bang, M., Korsgaard, A., Nielsen, M. P., & Kær, S. K. (2006). Development of a 400 W High Temperature PEM Fuel Cell Power Pack: Fuel Cell Stack Test. In *Proceedings of the Fuel Cell Seminar 2006 Conference* Fuel Cell Seminar.

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Development of a 400 W High Temperature PEM Fuel Cell Power Pack : Fuel Cell Stack Test

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1 Introduction

When using pressurized hydrogen to fuel a fuel cell, much space is needed for fuel storage. This is undesirable especially with mobile or portable fuel cell systems, where refueling also often is inconvenient. A reformed liquid hydrocarbon based fuel, like methanol can reduce the storage volume considerably. In tab.1 a comparison of the characteristics of liquid methanol and compressed hydrogen (200 bars) is shown.

	Hydrogen (200 bars)	Methanol
Density	16,27 kg/m ³	793,8 kg/m ³
Lower Heating Value	120,1 MJ/kg	19,9 MJ/kg
Energy density (grav.)	33,4 kWh/kg	5,53 kWh/kg
Energy density (vol.)	542,6 kWh/m ³	4388 kWh/m ³

Table 1: Characteristics of hydrogen and methanol at 25°C. [Engineering Equation Solver]

It is seen that in spite of the high energy content per unit mass of hydrogen; methanol has a clear advantage when it comes to volume, containing about 8 times more energy by volume.

Fuelling Nafion based low temperature PEM (LTPEM) fuel cells with pure hydrogen shows good performance characteristics, but the fuel cell membranes often show severe intolerance to reformat gas because of the presence of CO, which can result in poor fuel cell performance [1]. PBI (polybenzoimidazole) based high temperature PEM (HTPEM) fuel cells can operate stable at much higher CO concentrations. This makes a HTPEM fuel cell suitable for applications using a fuel reformer, and could simplify reformer design because CO removal is not needed. A fuel like methanol would be a preferable choice for reforming when using HTPEM fuel cells because of its high energy density and low reforming temperatures. The thermal integration and use of HTPEM fuel cells with methanol reformers has already shown promising results [2].

In a recent publication [3] the authors noted the absence of publications covering HTPEM fuel cell design and HTPEM fuel cell test station design. The work presented in the following seeks to demonstrate some of the issues related to these topics, with the motivations stated above. The use of a 30 cell HTPEM fuel cell stack is demonstrated, with a nominal power of $\approx 400\text{W}$ at $0,5\text{ A/cm}^2$. This very simple system design demonstrates some of the advantages and disadvantages in using the HTPEM PBI membrane technology in making a reliable simple fuel cell system.

2 Experimental setup

A schematic of the experimental setup can be seen in fig. 1L. The anode is running on pure hydrogen at a constant pressure and the cathode on atmospheric air.

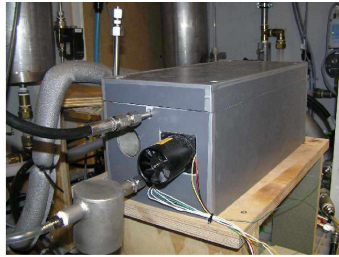
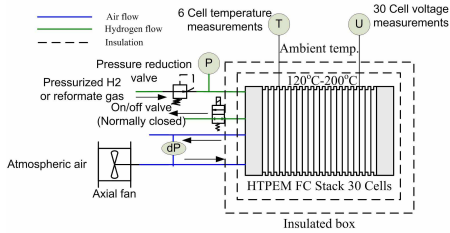


Figure 1: Left: Schematic of the fuel cell system. Right: Picture showing a HTPEM stack prototype.

Pure hydrogen is initially used as anode fuel, to gain performance results and further system control information on an operating HTPEM fuel cell stack. The hydrogen is held at a constant pressure of $\approx 0,2$ bars in the stack, by a pressure reduction valve. An occasional purging (every 5-15 min) is made to remove eventual impurities. When the fuel cell is to be operated on a reformat gas, this strategy is not necessarily the best way to fuel the stack, because of the CO presence in the reformat gas, instead a small overstoichiometric anode supply could be used. A great advantage of the HTPEM fuel cells is that they are much more tolerant to CO poisoning [4]. In fig. 1R a 30 cell prototype HTPEM stack is shown. The fuel cells used are PEMEAS CELTEC-P with an active area of 45.16cm^2 . To greatly simplify the fuel cell system, the fuel cell stack is designed with cathode air cooling. This stack design fulfills the desire of minimum parasitic losses, by the possibility of using a low power consumption cathode air supply. This is achieved by using a low power blower using $\approx 3\text{W}$ at nominal capacity, see fig. 1L. Another advantage of the blower compared to other blowers, is fast response, because of a low moment of inertia. The nominal voltage, current and power of the system is respectively: $17,7\text{V}$; $22,5\text{A}$; 400W . The operating temperature is $120\text{-}200\text{ }^\circ\text{C}$. CO tolerance is several percent.

The reason for the high operating temperatures is to avoid liquid water, when using a PBI fuel cell membrane. Liquid water present in the membrane will flush the phosphoric acid doped for increased proton conductivity [5], out of the cell.

3 Initial tests

Initially the air side of the stack is connected to a mass flow controller (MFC) and the stack is characterized with regards to differential pressure as a function of the air flow, the resultant graph is shown in fig. 2L. Different air stoichiometry points are marked on the curve, at $0,2\text{ A/cm}^2$.

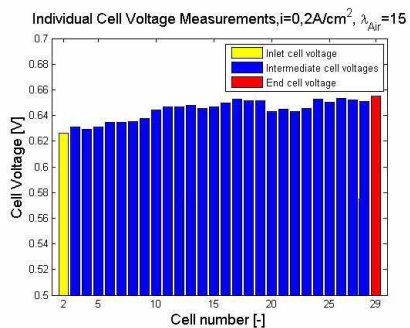
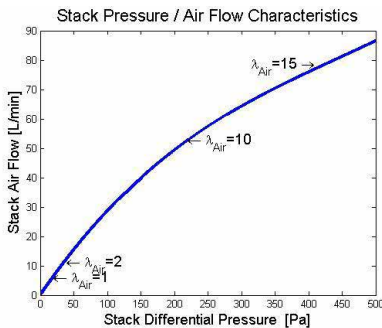


Figure 2: Left: Pressure as a function of flow of the 30 cell HTPEM stack. Right: Cell voltage distribution of HTPEM stack at $0,2\text{ A/cm}^2$.

Notice the very high stoichiometry of 15, at $0,2\text{ A/cm}^2$, because of the cathode cooling. After this initial

test, the cathode air blower can be mounted and the air flow can be controlled with a feedback of the differential stack pressure. When applying a load to the stack, the stack temperature will also be used to control the cooling requirement. At low current densities, the heat generated is equal to the heat lost by convection and conduction. For higher current densities, the stack needs cooling to avoid the temperature from rising above the operating temperature limit.

4 Experimental results

The actual operation of the HTPEM stack includes a warm-up mode, a current loading mode and a cool down and shut-down mode. The experimental test results presented here will primarily concern the current loading mode of the system.

The warm-up mode of the system includes raising the temperature of the fuel cell stack, to above 120°C. This is done by external heating sources and monitored with 6 thermocouples at different locations in the stack. 2 at the inlet cell, 2 in the middle cell and 2 in the last cell. At each of these three temperature measuring points, one thermocouple is situated in the top of the fuel cell and one is in the bottom in a small recess. The warm-up time of the stack can be quite long, depending on the heat supplied; more improvements are needed if minimization of this time is desired.

When above 120 °C current can be drawn from the fuel cell stack. When loading the stack, heat is generated and the temperatures will start increasing. This results in differences in cell voltages because of different temperatures. In fig. 2R the cell voltages of the stack are shown at steady-state temperatures at 0,2 A/cm².

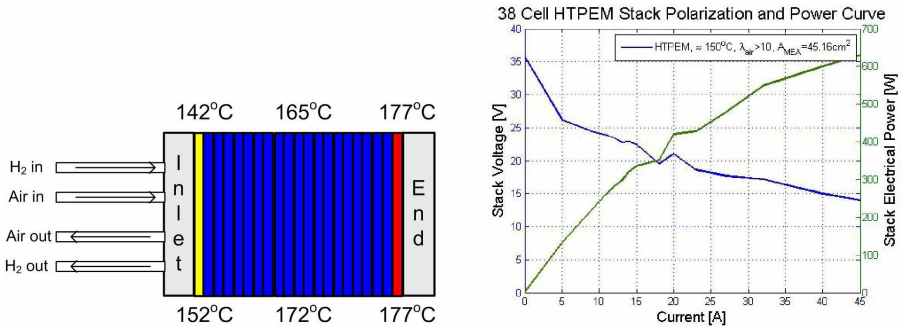


Figure 3: Left: Stack temperature distribution at constant load of 0,2 A/cm² and $\lambda_{air} \approx 15$. Right: Polarization curve of 38 cell HTPEM stack.

As seen in fig. 2R, the highest fuel cell voltage is 0,657 V and the lowest 0,626 V. This is due to the temperature differences in the fuel cell stack. In fig. 3L, the steady-state fuel cell stack temperature distribution is seen, without external heating, running at a constant air stoichiometry of ≈ 15 at 0,2 A/cm². It is seen that the highest temperatures, as expected, are in the end of the stack, opposite the cathode inlet due to better insulation. At the end of the stack, the local fuel cell temperature is uniform at $\approx 177^\circ\text{C}$ both in the top and the bottom. In the middle of the fuel cell stack, the top and bottom temperatures differ by a few degrees, 165°C and 172°C respectively. There is a large temperature difference at the inlet fuel cell, the top where the cold cathode air enters being 142°C and the bottom where the hot air exits being 152°C. This is caused by the high air flow entering the inlet end plate, cooling it, and also the fact that the inlet of the stack is less well insulated.

If all cells of the stack had the same cell voltage as the fuel cell with the highest temperature, the stack voltage would be 19.65V, instead it is ≈ 18.6 V, a loss of about 1V, which is 9W.

A polarization curve has been made on a stack of the same design but with 38 cells. The curve has

been made at steady-state temperatures with a manual adjustment of the cooling. This explains the stack voltage jumps seen in the curve in fig. 3R.

For purposes of later tests on control strategies, a temperature dependent steady-state model of the HTPEM fuel cell voltage is derived from the work of [4], as an input for a dynamic model of the average fuel cell stack temperature. This model is implemented in Simulink and verified against the experimental results.

5 Conclusions

The experiments made on the 30 cell HTPEM stack have resulted in more knowledge on the different issues involved during operation. This includes information on stack and single cell temperature distribution, single cell voltages during operation, the use of overstoichiometric cathode air cooling and dead end hydrogen operation on a HTPEM stack.

The experimental results indicate that the use of cathode air cooling simplifies the system greatly, and can result in very simple and robust fuel cell systems. When making a stack with a low pressure drop, it is possible to use fast low power consuming blowers.

The differences in temperature distributions in the fuel cell stack is small except at the inlet fuel cells at $0,2 \text{ A/cm}^2$. These temperature differences will be much larger at higher current densities and should be considered when designing the fuel cell stack and determining nominal operating conditions on a system level.

More work must be made on different warm-up strategies, minimizing the startup time.

Future work includes the design of a heat management control system, controlling the startup and operation of the fuel cell stack and monitoring the state of the system. Moreover, general derivation and testing of different control strategies for the fuel cell system both via modeling and experimental verification should be performed.

The system is to be tested with a DC/DC converter, looking at the load following capabilities of the HTPEM fuel cell system, and the possibilities of using it in a power pack module for a mobile application.

Different load cycle tests are also planned while running the HTPEM stack with a reformate gas. The temperature control will be critical when running with a reformate gas, so a model based control design will be used in order to design the heat management of the system.

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