Design and experimental characterization of a 350 W High Temperature PEM fuel cell stack

Nicola Zuliani
University of Trieste, Department of Mechanical Engineering , via A. Valerio 10 34127 Trieste
nzuliani@units.it

ABSTRACT. High Temperature Proton Exchange Membrane (HT PEM) fuel cell based on polybenzimidazole (PBI) polymer and phosphoric acid, can be operated at temperature between 120 °C and 180 °C. Reactants humidification is not required and CO content up to 2% in the fuel can be tolerated, affecting only marginally performance. This is what makes HT PEM very attractive, as low quality reformed hydrogen can be used and water management problems are avoided. Till nowadays, from experimental point of view, only few studies relate to the development and characterization of high temperature stacks. The aim of this work is to present the main design features and the performance curves of a 25 cells HT PEM stack based on PBI and phosphoric acid membranes. Performance curves refer to the stack operating with two type of fuels: pure hydrogen and a gas mixture simulating a typical steam reformer output. The stack voltage distribution analysis and the stack temperature distribution analysis suggest that cathode air could be used as coolant leading to a better thermal management. This could simplify stack design and system BOP, thus increasing system performance.

KEYWORDS. High Temperature PEM Fuel Cells; Experimental analysis; PBI; Hydrogen.

INTRODUCTION

A fuel-cell power-source system can generate electrical power with significantly improved: efficiency, energy density, ergonomics and environmental compliance (low or no emissions) than other conventional power sources. Amongst all types of fuel cells Proton Exchange Membrane (PEM) fuel cells have drawn the most attention because of their high power density (> 1 kW/kg), simple design and quick start. Usually, PEM fuel cells work at low temperature (< 100 °C) and are commonly called Low Temperature PEM (LT PEM) fuel cells. Several technical obstacles hinder their widespread commercialization. These include a complex water and heat management and the intolerance to CO usually contained in the reformates fuels. To overcome these problems research has focused on the development of PEM fuel cells that can be operated above 100 °C (High Temperature PEM fuel cells, HT PEM) [1, 2]. There are several advantages in operating at higher temperatures: (i) water management can be simplified because only a single phase of water need to be considered; (ii) the cooling system is simplified due to the increased temperature gradient between the fuel cell stack and the coolant; (iii) waste heat can be recovered as a practical energy source; (iv) CO tolerance is considerably increased thereby allowing fuel cells to use lower quality reformed hydrogen.
Amongst all types of HT PEM, the ones based on polybenzimidazole (PBI) and phosphoric acid membranes are the most promising. They can be operated at temperature between 120 °C and 180 °C, reactants humidification is not required and carbon monoxide (CO) content up to 2% in fuel can be tolerated, affecting only marginally the performance.

In literature the major research effort on this kind of fuel cells relate to the study, development and modelling of the high temperature membrane or the single fuel cell system [3-7]. For example Korsgaard et al. [7] studied the performance of a PBI and phosphoric acid based single cell operated with pure hydrogen and five types of reformates, containing up to 5% of carbon monoxide. They found that, for temperatures above 160 °C, the cell could operate with good performance with reformates containing up to 2% of CO. Similar results were obtained by the authors of this paper for a single fuel cell system [8]. Several literature papers refer to membrane degradation issues [9-12], but only some studies relate to the experimental analysis of the HT PEM fuel cell stack [13, 14]. Stacks usually show lower performance when compared to the single fuel cell system. This could be related to several factors as: a non uniform distribution of reactants inside each cell, a non uniform temperature distribution, an increased electrical resistivity. With the aim of experimental analyze an HT PEM fuel cell stack, this work present the main design features and the performance curves of a 25 cells HT PEM stack based on PBI and phosphoric acid membranes, focusing on voltage and temperature distribution.

STACK DESIGN

The stack design relies on some features that were already tested with good results during a previous single cell experimental activity [8]. The stack, has 25 cells fed in parallel. Each cell contains a commercial PBI BASF Fuel Cell Celtec P-1000 MEA, two bipolar plates and the gaskets which seal the active area and the reactant manifolds (see Fig. 1). The MEAs have an active area of 50 cm² and an average thickness of 860 μm. The membrane is about 60 μm and has a phosphoric acid content of more than 95 wt% in a PBI matrix. The platinum catalyst loading is 0.75 mg/cm² on the cathode and 1 mg/cm² on the anode [15]. The plates were designed and built by the authors, using Sigracet BPP4 graphite plates, that can withstand a maximum operating temperature of 180 °C [16]. Each plate contains the flow field pattern and the air cooling channels. The reactant flow field has a multiple serpentine pattern with five square section channels. The cells are stacked and assembled between two steel square end plates, fixed with eight all threaded tie rods (see Fig. 2). Belleville spring washers were used at one side of the tie rod and the stack was tightened to a maximum torque of 7 Nm.

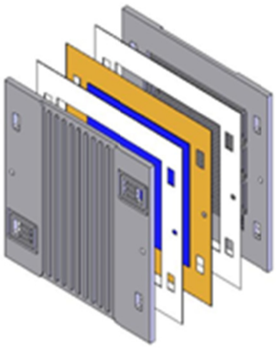

Figure 1: Exploded view of the single HT PEM cell.

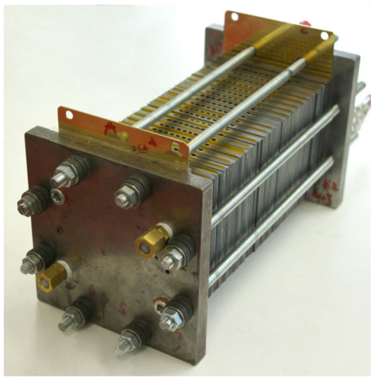

Figure 2: Picture of the 25 cells HT PEM stack designed at the Mechanical Department of the University of Trieste.

TEST BED

The stack experimentation was carried out on a test bench, schematically presented in Fig. 3. Two Baumer pressure transmitters are used to measure the reactants inlet pressures. The stack temperature is measured using 6 K-type thermocouples fitted on the lower and on the upper part of the stack. Reactants flow rates were measured and controlled using two mass flow controllers: a Sierra SmartTrack M100 for the air circuit and a Bronkhorst El-Flow F201 for the hydrogen circuit. Load is controlled by a Thurlby Thandar Instruments TTi LD 300 electronic load module, operated in constant current mode. A measurement and control system, based on the National Instruments CompactRIO hardware, was used to control the stack main operating parameters (reactants flows, temperature) and to acquire the experimental data.

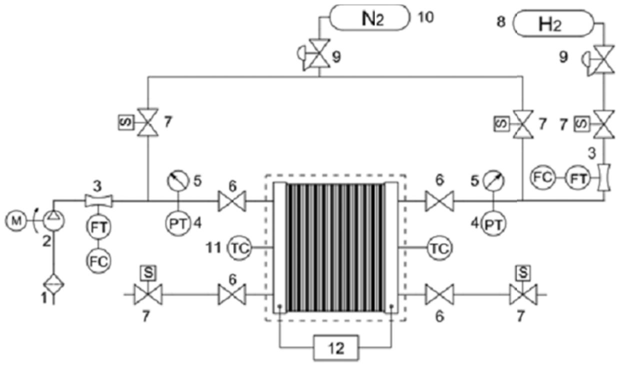

Figure 3: Schematic representation of the test bed (1-air filter, 2-air compressor, 3-flowmeter, 4-pressure transmitter, 5- pressure gauge, 6-valve, 7-solenoid valve, 8-hydrogen cylinder, 9-pressure regulator, 10-nitrogen cylinder, 11-thermocouple, 12-electronic load).

The CompactRIO hardware, consisting of the NI cRIO 9004 real time controller and the NI cRIO 9104 chassis, was configured with modules dedicated to specific tasks: analog input for voltage and current measurements, thermocouple input, analog output for mass flow controls and digital output for temperature control. Single cell voltages were measured using a NI cRIO 9201 and NI cRIO 9206 analog input modules. Stack temperature distribution has been measured using a Agema Thermovison 570 infrared camera.

EXPERIMENTAL PROCEDURE

A start up and shutdown procedure were implemented in order to avoid water condensation and membrane degradation. During the start-up procedure the fuel cell stack is heated up from room temperature to at least 120 °C using an external hot air blower. During the shut-down procedure, the stack was set in Open Circuit Voltage (OCV) and purged with nitrogen, on both anode and cathode sides. At normal operation, the stack mean temperature was controlled, using an on/off algorithm. The control system acted on the hot air blower or on the cooling fan. Polarization curves were collected operating the stack at 160°C with two different fuels: pure hydrogen and a gas mixture simulating a typical steam reforming reformate: H_2 56.35%, CO 0.5%, CO_2 43.15 %. Stack voltage was measured starting from OCV until the lowest stack cell voltage reach about 0.3 V. Single cells voltages were measured at 200 and 400 mA/cm^2. Temperature distribution was observed operating the stack with pure hydrogen at 400 mA/cm^2 current density load. The infrared camera was pointing the top side of the stack.

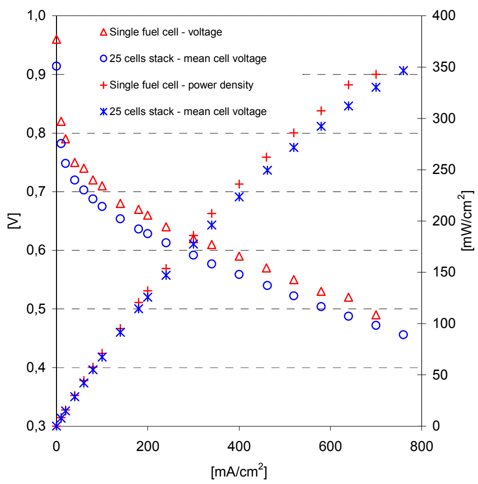

Figure 4: Polarization curves and power density variations with load for the 25 cells stack and for a single fuel cell [8]. Stack and single cell mean temperature: 160°C. Fuel: H_2.

STACK PERFORMANCE OPERATING WITH HYDROGEN

Fig. 4 shows the stack polarization curve and the stack power density variation with load operating with pure hydrogen at 160°C. In the same figure the polarization curve and the power density variation with load for a single fuel cell [8] at the same operating conditions is included. The stack has a nominal power of 365 W at 0.5 V mean cell voltage, corresponding to a power density of 292 mW/cm². The maximum reached stack power has been 433 W at 0.46 V mean cell voltage. As expected stack performance is lower than single cell performance. Performance difference decreases as load increases: for example operating at 0.6 V power density is 221 mW/cm² for the single fuel cell and 162 mW/cm² for the stack (27% less). At 0.5 V power density is 338 mW/cm² for the single fuel cell and 292 mW/cm² for the stack (14 % less).
This behaviour could be explained referring to the stack temperature distribution: at low loads the heat dispersion through the end plates causes a marked stack temperature non uniformity (see Fig. 8). As performances depend on temperature [1, 2], cell voltages are lower at stack ends. Increasing stack load tends to decrease temperature non uniformity thus improving performance.

STACK PERFORMANCE AND VOLTAGE DISTRIBUTION OPERATING WITH HYDROGEN AND REFORMATE FUELS

Fig. 5 shows the mean cell voltage and mean power density variation with load for the stack operating with hydrogen and the simulated reformate at 160°C. Referring to Tab. 1 performance differences between the 2 types of fuels are 5% at 200 mA/cm² and 9% at 400 mA/cm². Stack performance related to reformate operation are only to some extend lower than that with hydrogen as previously observed in [7, 8] where a single fuel cell has been investigated. Furthermore, due to the CO poisoning effect, performance difference increases as load increase [17].
An important aspect regarding the stack operation is the voltage non-uniformity, since the lowest voltage cell will limit the performance of the entire stack. Fig. 6 shows the stack voltage distribution at 200 mA/cm² and 400 mA/cm². Several observation can be made:

- ✓ stack voltage distribution patterns are similar both for the hydrogen and reformate case;
- ✓ stack voltage distribution follows a parabolic pattern that is similar to that of the stack temperature profile shown in Fig. 8;
- ✓ the ends cells exhibit the lowest voltages;
- ✓ at 400 mA/cm², the cell number 1 reach a very low voltage of 0.326 V when the stack is fuelled with reformate.

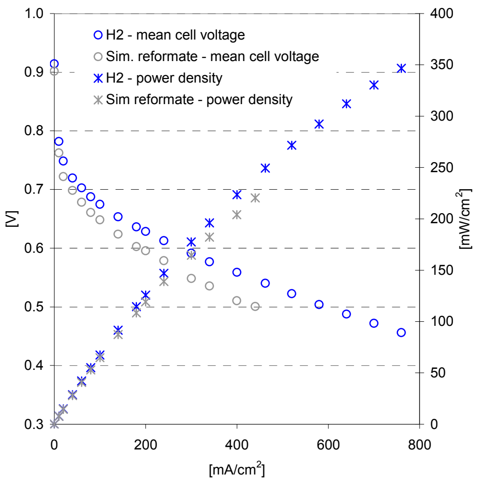

Figure 5: Mean cell voltage and power density variation with load. Stack mean temperature 160°C. Fuels: H_2 and simulated reformate (H_2 56.35%, CO 0.5%, 43.15 % CO_2).

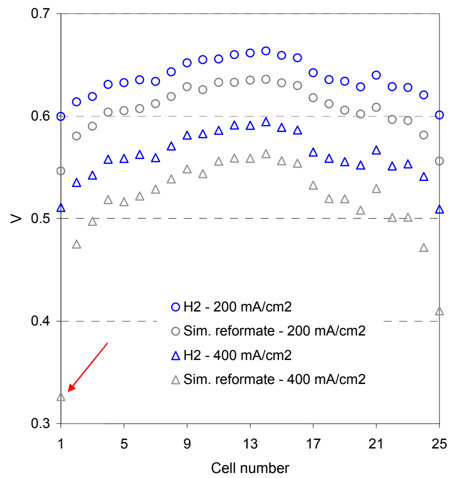

Figure 6: Voltage distribution at 200 mA/cm² and 400 mA/cm². Stack mean temperature 160°C. Fuels: H_2 and simulated reformate (H_2 56.35%, CO 0.5%, 43.15 % CO_2).

Current density [mA/cm²]	hydrogen			reformate		
	Mean cell voltage [V]	Mean cell power density [mW/cm²]	Stack power [W]	Mean cell voltage [V]	Mean cell power density [mW/cm²]	Stack power [W]
200	0.63	126	157	0.60	119	149
400	0.56	223	279	0.51	204	255
580	0.50	292	365	-	-	-

Table 1: Performance differences at 200 and 400 mA/cm² for the stack operating with hydrogen and reformate as fuel.

The voltage distribution follows a parabolic pattern that is similar to the stack temperature profile (see Fig. 8). This is due to the temperature dependent performance of the single PBI/H_3PO_4 based fuel cell. Voltage differences between adjacent cells could be related to the different reactant distribution along the stack.
The voltage non-uniformity becomes even more noticeable when fuels containing CO are used. In fact the CO poisoning effect is strongly associated to cell temperature [17]. In this case the first stack cell (see red arrow in Fig. 6) presents the lowest voltage due to the combined effect of CO content in the fuel and low cell temperature. In the case of operating with reformate fuels stack temperature distribution is crucial in order to obtain best performance.

STACK TEMPERATURE DISTRIBUTION

Fig. 7 and Fig. 8 show the temperature distribution along the stack operating with pure hydrogen at 160°C stack mean temperature and 400 mA/cm² current density load. There is a marked temperature difference between central and end stack parts (about 20°C). The heat dispersion through the end plates could explain this temperature behaviour. It is also possible to observe the temperature differences amongst the 3 sections of the stack named T1, T2 and T3 (Fig. 7 and Fig. 9). T1 temperature is the lowest compared to T3 and T2. Differences are higher at the stack middle reaching 25°C between T1 and T2. This temperature behaviour could be explained referring to the cathode air cooling effect. In fact, reactant air enters the stack from the T1 section and leave from the T3 (Fig. 9).

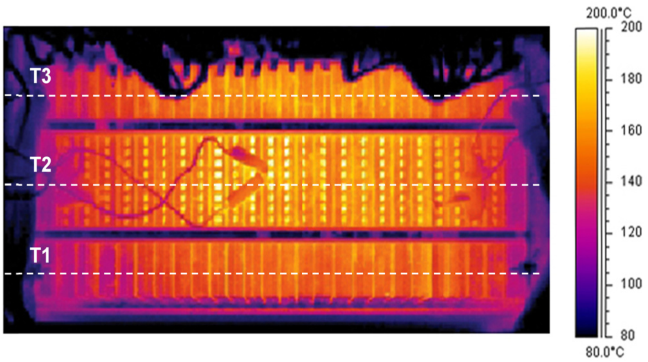

Figure 7: Thermal image of the 25 cells HTPEM stack. Current density 400 mA/cm², mean stack temperature 160°C, fuel: pure hydrogen.

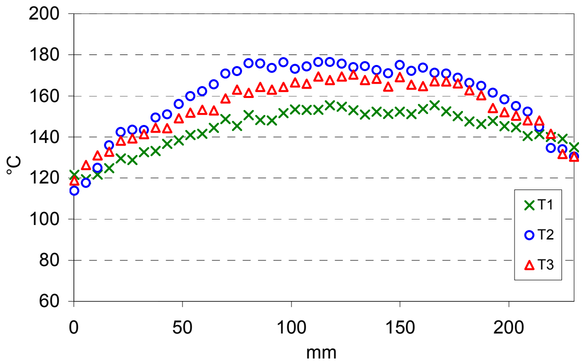

Figure 8: Stack temperature profile. Current density 400 mA/cm², mean stack temperature 160 °C, fuel: pure hydrogen.

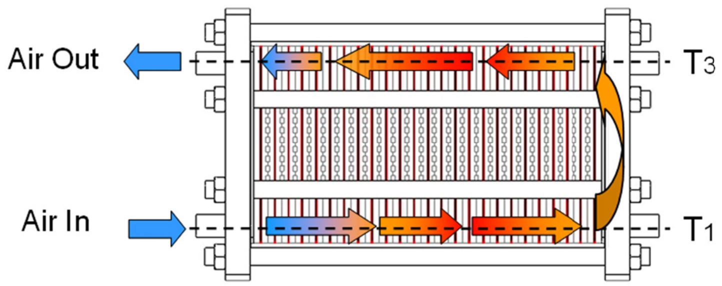

Figure 9: Simplification scheme of the air path through the fuel cell stack.

This simple investigation suggests the opportunity of using cathodic air as coolant in order to manage the stack temperature and reach a better temperature distribution. Additionally, the BOP of the system can be simplified as only a single blower could be used for cathodic air supply and coolant purpose. It is significant to highlight that this BOP simplification could not easy apply to a low temperature PEM fuel cell based system where humidification requires a more complex balance of plant.

Conclusions

In this paper the main design characteristics and an experimental analysis of a 25 cells HT PEM stack are presented. The stack can deliver about 350 W at 0.5 V mean cell voltage when operated with pure hydrogen. When operated with reformate stack performance decreases only slightly. This performance behaviour has been found similar to that of a single fuel cell system. As expected stack performance is lower than single cell performance.

The stack voltage and temperature distribution analysis reveal that temperature management has a key role in order to reach the best performance particularly when operating with reformates. It has been observed that cathode air affects stack temperature distribution noticeably suggesting the opportunity to use it for temperature management purpose. This design improvement could lead to a simpler BOP as only a single blower could be used for air supply and cooling purpose.

References

[1] J. Zhang, Z. Xie, Y. Tang, C. Song, T. Navessin, Z. Shi, D. Song, H. Wang, D. P. Wilkinson, Z. S. Liu, S. Holdcroft, J. of Power Sources, 160 (2006) 872.
[2] Q. Li, J. O. Jensena, R. F. Savinell, N. J. Bjerrum, Progress in Polymer Science, 34 (2009) 449.
[3] D. F. Cheddie, N. D.H. Munroe, J. of Power Sources, 160 (2006) 215.
[4] K. Scott, S. Pilditch, M. Mamlouk, J. of Appl. Electrochem., 37 (2007) 1245.
[5] O. Shamardina, A. Chertovich, A.A. Kulikovsky, A.R. Khokhlov, Int. J. of Hydrogen Energy, 30 (2009) 1.
[6] M.K. Daletou, N. Gourdoupi, J.K. Kallitsis, J. of Membrane Science, 252 (2005) 115.
[7] A. R. Korsgaard, R. Refshauge, M. P. Nielsen, M. Banga, S. K. Kæra, J. of Power Sources, 162 (2006) 239.
[8] R. Taccani, R. Radu, Z. Nicola, A. Damnjanovic, In: Proceedings of the European Fuel Cell Technology & Applications, EFC 09-17056 (2009).
[9] H. Tang, Z. Qi, M. Ramani, J. F. Elter, J. of Power Sources, 158 (2006) 1306.
[10] J. Hu, H. Zhanga, Y. Zhaia, G. Liua, B. Yia, Int. J. of Hydrogen Energy, 31 (2006) 1855.
[11] Z. Qi, S. Buelte, J. of Power Sources, 161 (2006) 1126.
[12] A.D. Modestov, M.R. Tarasevich1, V.Ya. Filimonov, N.M. Zagudaeva, Electrochimica Acta, 54 (2009) 7121.
[13] J. Scholta, M. Messerschmidt, L. Jörissen, Ch. Hartnig, J. of Power Sources, 190 (2009) 83.
[14] S. J. Andreasen, S. K. Kær, Int. J. of Hydrogen Energy, 33 (2008) 4655.
[15] T. J. Schmidt, J. Baurmeister, J. of Power Sources, 176 (2008) 428.
[16] Sigracet BPP Datasheet, Eisenhuth GmbH, (2004).
[17] Q. F. Li, R. H. He, J. A. Gao, J. O. Jensen, N. J. Bjerrum. J. Electrochem. Soc., 150 (2003) 1600.