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The Impact of Humidification Temperature on a 1 kW Proton Exchange Membrane Fuel Cell Stack

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Abstract

The importance of water management in proton exchange membrane fuel cells is discussed in this paper. First part of research is dedicated to the characterization of a water-cooled 1kW PEMFC fuel cell stack at different operating conditions with calculation of net electric and thermal efficiencies. In the second part, the influence of inlet air humidification temperature at various loads and operational conditions was experimentally found. It was observed that humidification temperature in the air saturator has a strong impact on cell performance and this impact is growing with current density. Increase in humidification temperature by 8°C at 200mA/cm^2 raised cell voltage only by 0.01V, while at 500mA/cm^2 the same change led to 0.04V growth. Additionally, the effect of change of air stoichiometry on this relationship is studied. Increased air stoichiometry led to a maximum growth of the slope angle by 68% at 500mA/cm^2.

Keywords: Absolute humidity; Humidification Temperature; PEM fuel cell; Polarization curve; Relative Humidity; Water management

1. Introduction

Proton exchange membrane fuel cell (PEMFC) is a promising micro-cogenerative solution for autonomous power supply in remote residential areas. Coupled with methane reformer it can reach up to 42% electric efficiency excelling conventional micro-cogenerative units [1]. One of the most crucial problems, which inhibits the commercialization of PEMFC-based power systems, is fuel cell water management. Many scientific works are dedicated to the investigation of the influence of air relative humidity (RH) and operational temperature on cell performance [2-4]. D. H. Jeon et al. [4] performed CFD simulation of a 300cm^2 cell at various RH levels. He considered the influence of relative humidity independently from air temperature, which does not give us an information about the actual amount of water entering the cell. W. M. Yan et al. [5] in turn, investigated cathode and anode humidification temperatures on cell performance.

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The experiments were performed for two Nafion membranes with different thicknesses at 30, 65 and 80°C cell temperatures. All experiments were made at constant humidification temperatures within all current density range. Such approach cannot guarantee the best fuel cell performance because different electric load may require operation with different absolute humidity.

Several papers are focused on the development of mathematical models describing water balance in PEMFC [8-11]. These models are mainly validated for single cell configurations, and usually, such results cannot be scaled up for stacks. Some researchers are focused on the development of methods to detect cell flooding [14-15]. S. Toscani et al. [14] in his paper compared two different methods for detecting cell flooding. He distinguishes certain advantages of the method based on a pressure difference between cathode inlet and outlet, comparing it with traditional electrochemical impedance spectroscopy (EOS). It was noticed that after increasing the RH of inlet air, pressure increases with good response. While voltage drop due to flooding comes later, and the relationship between voltage drop and pressure increase is not clear. Thus, measurement of pressure drop is a good way to detect flooding and prevent it before voltage drop, but it cannot be used to estimate fuel cell performance.

The present study aims to highlight the importance of humidification system, which is composed by an air-water saturator of bubbling tank type with temperature control, discussing the effect of the operating temperature and its relationship with the cell current density. The research was performed on a commercial 1kW FC stack (S1-10C Power Cell Sweden AB) with 10 cells of 200cm^2 active surface area ready for applications. Usually, humidification systems are analyzed separately from fuel cells and thus, the results of such experiments are not always applicable to real systems [3, 12-13]. The saturator humidification temperature turns out to be a key parameter, being it directly related to the cathode inlet absolute humidity, rather than relative humidity, and influencing also the cell inlet temperatures. Therefore, in this paper humidification temperature is chosen to be the main variable of the experiment.

Nomenclature

P	Pressure, bar
T	Temperature, °C
RH	Relative humidity, %
λ	Stoichiometric coefficient, -
m_{H2}	Mass flow rate of hydrogen, g/s
m_w	Mass flow rate of water, g/s
T_{in_w}	Inlet water temperature, °C
T_{out_w}	Outlet water temperature, °C
Cp	Specific heat of water, kJ/kgK
Pel	Electric power, W
LHV	Lower Heating Value, kJ/g

2. Experimental set-up

The layout of experimental set-up, placed at the Laboratory of Micro-Cogeneration of Politecnico di Milano, is shown in Fig.1. S1-10C PEMFC stack consists of 10 cells of 200cm^2 active surface area with 1kW total generated electric power. The fuel cell is connected to a programmable DC load (Chroma 63204A), which can be supplied with both current and voltage input. The FC has three inlets and three outlets for hydrogen, air, and cooling media. Deionized water is used, as cooling media, to keep a stable operational temperature of the stack and recovering heat for potential cogeneration purposes. During the start-up procedure a isothermal bath heats up inlet water until 70°C, heat exchanger HX-304 collects excess heat generated by chemical reaction and cools down the water flow until the required operational temperature is reached. Hydrogen comes from a high-pressure vessel with a purity of 4.5. Hydrogen inlet flow is controlled by a mass flow controller (IN-flow Bronkhorst) while the inlet FC pressure is kept between 1.2 -1.5 bar by means of a control valve placed at the stream outlet. During the start-up and shut-down procedures, nitrogen gas is used to flush the FC in order to remove any contaminations or flammable gases from the reaction zone. When the system is ready to be connected to the load, nitrogen is switched to hydrogen. At the outlet, unreacted air, excess hydrogen and water are purged to the ventilation system.

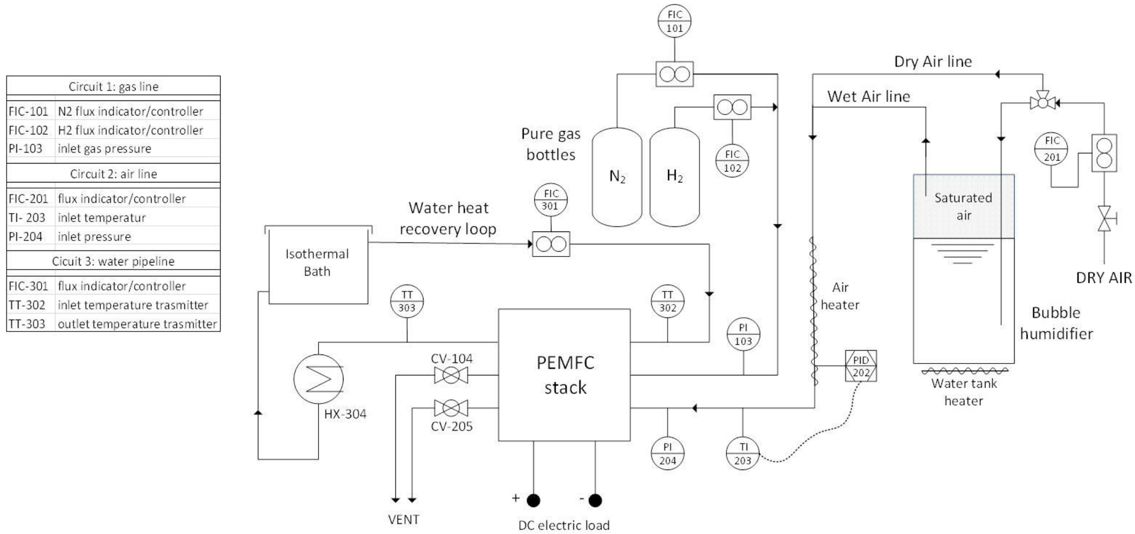

Fig. 1. The layout of the experimental set-up.

Dry air entering the system is regulated by a flow controller FIC-201 keeping inlet air pressure in the range going from 1.2 to 1.5 bar. After a three-way valve, the air goes directly to the PEMFC stack or passes through the bubble humidifier. The dry air loop is necessary at the start-up and shut-down procedure. Air enters a saturator composed by a heated reservoir bubbling through the water column. It leaves the reservoir once it is heated to the required temperature and humidified up to 100% relative humidity. Afterwards, air passes through a line, which is heated at a temperature 2-3°C higher than inside the water reservoir. This allows avoiding water condensation before and at the cell entrance. The temperature on the heating line can be regulated by controller PID-202, which shows the temperature detected by thermocouple TI-203.

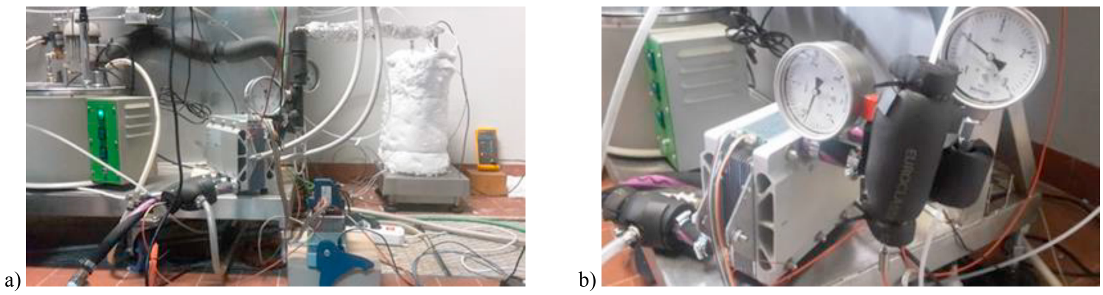

Fig. 2. (a) Test facility; (b) Zoomed photo of FC stack.

3. Methodology

Fuel cell operation was characterized in the current density range of 0-600 mA/cm^2. Using Equation (1), hydrogen and air volumetric flow rates (Nl/min) for different loads were calculated [17]:

$$v = \frac{Q \cdot n \cdot \lambda \cdot I}{C \cdot 1000} \tag{1}$$

where Q is reactant flow rate, Nl[†]/cell/A/min (Q_{H2} =7, Q_{air} =16.6)[‡]; n is the number of cells; I is the current, A; λ is the stoichiometric coefficient[§]; C is the hydrogen mole fraction equal to 1.

According to the manufacturer [17], stoichiometric coefficients for the air λ_{air}=2.5 and hydrogen λ_{H2}=1.5 are recommended. As can be observed from Fig. 3(a), at such conditions there is a rapid voltage drop at the current densities above 500 mA/cm^2. It can be explained by reduced membrane conductivity caused by insufficient humidification. Strong air flow bubbling through the humidifier leaves the system with lower amount of water. In order to maintain full humidification at all current density range, it was decided to reduce air stoichiometry λ_{air} to 2.2. Fig. 3(a) shows that such change almost does not influence voltage below 500 mA/cm^2, but improves the performance above 500 mA/cm^2. Moreover, to increase system efficiency, hydrogen stoichiometry was reduced to 1.4. Thus, fuel cell characterization was performed for two modes, which parameters can be seen in Table 1.

Table 1. Parameters for PEMFC stack

Parameter	Nominal conditions	Proposed in this work
Air inlet pressure, bar	1.25	1.3
H_2 inlet pressure, bar	1.20	1.3
FC Operational temperature, °C	70	70
Air stoichiometry	2.5	2.2
H_2 stoichiometry	1.5	1.4
Maximum load, A	120	120

In order to compare the performance of the cell at two different operational modes, total efficiency was calculated as the sum of electric and thermal efficiencies considering consumed hydrogen with lower heating value LHV_{H2} equal to 120 kJ/g. Electric efficiency η_{el} depends on DC electric power output $P_{el,DC}$ while thermal efficiency η_{therm} of the stack depends on the water cogeneration loop temperature difference between inlet $T_{in,w}$ and outlet $T_{out,w}$ assuming a constant water mass flow rate m_w = 50 g/s.

$$\eta_{el} = \frac{P_{el,DC}}{LHV_{H_2} \times \dot{m}_{H_2}} \tag{2}$$

$$\eta_{therm} = \frac{c_{p,w}\left(T_{out\_w} - T_{in\_w}\right) \times \dot{m}_w}{LHV_{H_2} \times \dot{m}_{H_2}} \tag{3}$$

After FC characterisation, experiments with different operation of external humidifier were performed. As mentioned, humidification system was designed to obtain a full humidification of the air entering the fuel cell: thus, knowing the humidification temperature, maximum absolute humidity φ_{max} can be easily derived [18]. Keeping RH close to maximum, but changing the absolute humidity via humidification temperature, yields changes in cell voltage, which can be determined for a broad range of current densities.

4. Results and discussion

Fig. 3(a) shows polarization curves obtained under nominal and proposed conditions. As it was discussed before, reduced stoichiometry did not worsen fuel cell performance at lower current densities, but improved it at higher current densities, ensuring saturation conditions. The voltage curves represent the average value of 8 cells, which are less sensitive to humidity rate (Cells 2-9). Maximum power achieved at the nominal conditions at current density of 600 mA/cm^2 is equal to 74.2 W/cell, that is 3 W/cell lower than at proposed conditions. Fig. 3(b) shows net electric and thermal efficiencies calculated for different loads at nominal conditions. Maximum total efficiency is equal to 94.1% at 300 mA/cm^2. At higher loads, the total efficiency is slightly lower due to voltage losses, caused by mass transport limitations. On the other hand, the bigger hydrogen consumption at higher current density increased the thermal power and as a consequence the thermal efficiency.

[†] Normal conditions defined at 0°C, 1 atm
[‡] Recommended values by manufacturer
[§] Stoichiometry defines the ratio between reactant feed (into the fuel cell) and reactant consumption (inside the fuel cell)

The influence of inlet air pressure is shown in Fig. 4. Pressurization significantly improves FC performance at the all current density range, as expected by the positive influence of pressure on the cell ideal voltage (Nernst voltage) [18]. However, the variation is influenced also by the changes in the air total humidity, as explained in the following section.

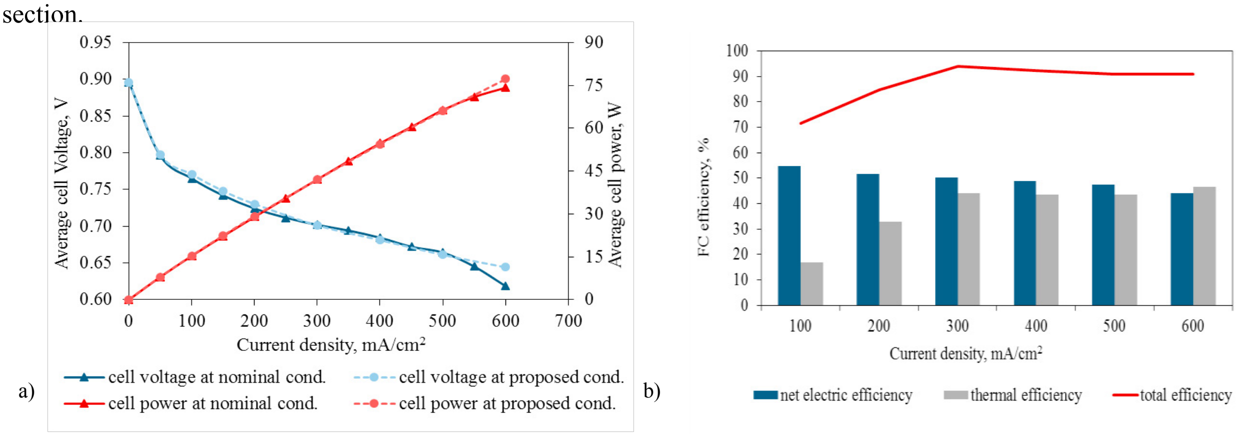

Fig. 3. (a) Polarization and power curve at nominal and proposed conditions; (b) Net electric, thermal and total efficiencies at nominal conditions.

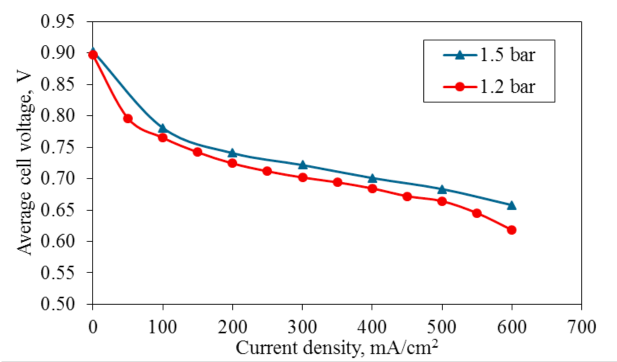

Fig. 4. The effect of operational pressure on FC polarisation curve

During the experimental work, it was observed that temperature of humidifier has a significant effect on FC performance. This effect is growing with the current density. Fig. 5 shows the influence of humidification temperature on cell voltage at 200, 400 and 500mA/cm^2. It is clear from the graph that humidification temperature increases cell voltage at all current densities but differently. A line slope, named here *b,* is growing by 37.5% from 200 to 400mA/cm^2 and by 56.8% from 400 to 500mA/cm^2.

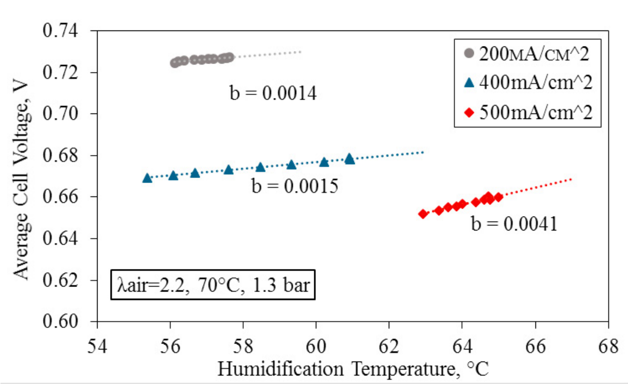

Fig. 5. The impact of humidification temperature on average cell voltage at 1.30 bar, λ_{air}=2.2 and 70°C.

The influence of humidification temperature on cell voltage depends on stoichiometric coefficients as well, though this dependency is well pronounced only at high current densities. FC characterization on Fig.3(a) showed that increase of the air stoichiometry λ_{air} from 2.0 to 2.5 does not change cell voltage at the current densities below 500 mA/cm^2. However, variation of humidification temperature leads to significant changes in cell voltage as it can be observed from Fig 6(a) and (b). At 400 mA/cm^2 increased stoichiometry combined with increased humidification temperature results significant growth in cell voltage whitout affecting the slope b. At 500 mA/cm^2 increased stoichiometry combined with reduced humidification temperature vice versa worsens cell performance, showing, on the other hand, a line slope 68% bigger for λair= 2.2 respect to the one at λair= 2.0. Further experimental tests are so required to investigate cell behavior under the combined effect of humidification temperature and air stoichiometry, especially at high current density values.

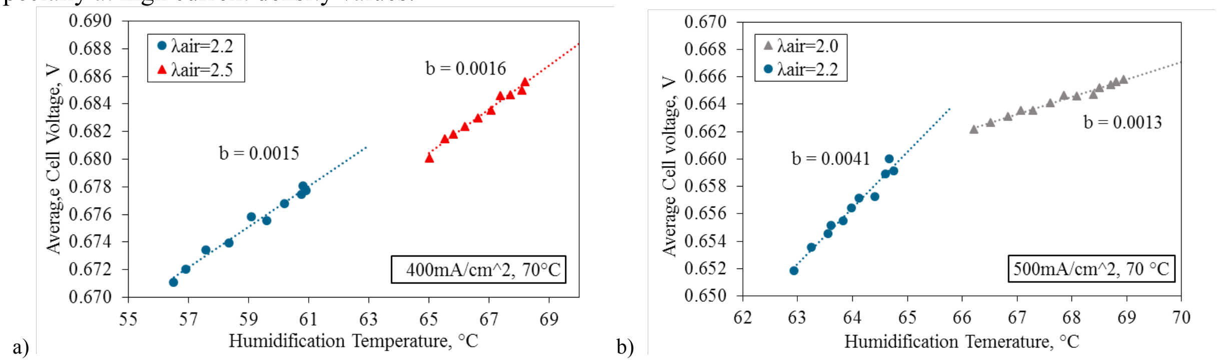

Fig. 6. The impact of air stoichiometry on change of cell voltage over humidification temperature at a) 400mA/cm^2 b) 500mA/cm^2.

5. Conclusion

This paper highlights the importance of inlet air humidification temperature for PEMFC-based energy systems. Humidification system was designed in such way that inlet air leaves humidifier fully saturated with 100% relative humidity. Experimental results showed the flowing trends:

- Increase in humidification temperature leads to increase in cell voltage at all current density range;
- The impact of humidification temperature is growing with the current density. At 200mA/cm^2, temperature increase by 8°C raised cell voltage only by 0.01V, while at 500mA/cm^2 it raised by 0.04V;
- Inlet air stoichiometry accelerates the impact of humidification temperature for 500mA/cm^2 load, but does not significantly influence it for lower current densities. It is planned to investigate this phenomena in more details.

Summarizing experiments, it is recommended to work at proposed operational conditions (T=70°C, P=1.3 bar, λ_{H2} =1.4, λ_{air}=2.2) to increase generated power at the current densities above 500 mA/cm^2. Moreover, humidification temperature should be increased together with the load starting from 50 °C at 50mA/cm^2 and growing up to 70°C at 600mA/cm^2.

Acknowledgements

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