Effect of the Temperature Distribution on the Performance of PEMFC Stacks for Fault Diagnosis

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Abstract — This paper presents the temperature distribution on a PEMFC stack which can be used for fault diagnosis. The effect of the temperature is considered on the performance of one single fuel cell both theoretically and experimentally. In order to validate the effect of temperature distribution, several tests were carried out with different operating conditions in one single cell. Thus, according to the variation of temperature, different parameters vary linked to the voltage losses and current density, recognized in the FC thermocouples installed in three different regions of stack FC. The results show good recognition for the considered faults in a stack PEMFC on the basis of temperature distribution.

Keywords: Fault diagnosis, PEMFC Stack, Temperature distribution.

Subscripts and superscripts

E	The reverse voltage
F	Faraday constant (96485 C Mol^{-1}).
i	Current density (A cm^{-2}).
I_{lim}	Limiting current density (A cm^{-2}).
i_o	Exchange current density (A cm^{-2}).
T	Temperature (K).
R	Gas constant (8.314 J Mol^{-1}K^{-1}).
V_{cell}	Fuel cell stacks voltage (V).
V_{act}	Activation polarization (V).
V_{con}	Concentration polarization (V).
V_{ohm}	Ohmic polarization (V).
P_{H2}	Partial pressure of hydrogen (Pa).
P_{O2}	Partial pressure of Oxygen (Pa).
P_{H2O}	Partial pressure of water (Pa).
σ_m	Conductivity in units (S cm^{-1}).
t_m	Thickness (cm^2).
n	Number of exchanging electrons per mole of reactant (2 for the PEM fuel cell).

Introduction

The Proton Exchange Membrane Fuel Cell (PEMFC) is considered as a very promising power generation module for the Fuel Cell Electrical Vehicle (FCEV), since it meets targets of high efficiency and low CO_2 emissions [1-4]. Operating conditions of a PEMFC have a significant effect on output power, long-term behavior, reliability and lifetime.

A study on the performance of PEMFC under variable temperature and relative humidity condition has been made in [5] and demonstrated that these parameters have a significant effect on the energetic performance of material and FC. Another paper [6] studied the effect of different operating conditions on the performance of PEMFC, such as operating temperature and different anode and cathode humidification temperature; the results showed that increasing operation temperature improves the performance of FC when enough humidification is implemented; moreover, by increasing the pressure, the performance of the FC improves. Also [7] investigated the operating condition in order to improve the performance of PEMFC and its results show that, even if the FC performance was affected by cathode humidification, the variation of temperature (60°C and 70°C) has less influence on the performance of the FC. Out of its different operating conditions, such as temperature, pressure, humidity and current density, that could affect FC performance, temperature seems to be one of the most important ones [8]. Indeed, heat control in a FC is a critical factor for increasing performance, durability and reliability of FC stacks [9-10].

Several papers have studied temperature variations and highlighted the influence of this parameter on the performance and lifetime of the FC: paper [11] studied the effect of humidification temperatures and operating temperature on the performance of a 300W fuel cell stack; its results indicate that membrane resistance is strongly affected by operating temperature and water content. In addition, it proved that the performance of the FC is enhanced by increasing temperature from 20°C to 40°C. Indeed, by increasing temperature, the gas diffusivity and membrane conductivity have been increased. In addition, increasing temperature makes the current density increase, which can in turn reduce the activation losses. Another paper [13] considers cell temperature and membrane humidity effects on the dynamic behavior of the PEMFC: its results show that the electrical output is affected by cell temperature and membrane humidification rate. Moreover, in [14] a nonlinear model of PEMFC has been developed that considers the effect of the temperature gradient and where it is mentioned that the most significant effect on the FC performance is related to the load and the operatingg temperature. Actually, temperature distribution seems to play a very important role in the apparition of “hot spots” that can enhance the mechanical stress for instance [15]. Other than the impact of temperature, this article attempts to find a technique based on temperature distribution in single cell and stack that is related to performances of the FC. This information is then used for fault detection.

It should be noted, however, that the above papers have studied the temperature effect on the performance of the FC stack without investigating the temperature distribution inside the cell as well as its effect on fault occurrence in the FC. This article focuses, on the variation of voltage due to temperature variations in a stack FC. In addition, all parameters are discussed in detail and validated by experimental tests in one single cell and in one stack of the FC. The advantage of this method is that it can be used for fault detection without measuring the voltage since it is only based on the recording of temperature variation in the FC stack. A significant benefit of this method is its simplicity and convenience since it only requires the use of thermocouples for fault detection.

This paper is organized as follows. The temperature effect on the polarization parameters is presented in section I, the test bench and components are described in section II and the results are shown in section III. Finally, conclusions are drawn in section IV.

I. TEMPERATURE EFFECT ON THE POLARIZATIONS PARAMETERS

The general equations for the calculation of the cell voltage are described as follows [16-17]:

$$V_{cell} = E - V_{act} - V_{ohm} - V_{con} \quad (1)$$

$$V_{cell} = \left(\frac{RT}{nF}\right)\ln\left(\frac{P_{O2}{}^{0.5}P_{H2}}{P_{H2O}}\right) - \left(\frac{RT}{nF}\right)\ln\left(\frac{i}{i_o}\right) - iR_m - \left(\frac{RT}{nF}\right)\ln\left(\frac{i_{\lim}}{i_{lim} - i}\right) \quad (2)$$

$$R_m = \frac{t_m}{\sigma_m} \quad (3)$$

$$\sigma_m = \frac{181.6(1 + 0.03(i/A) + 0.062(T/303)^2 (i/A)^{2.5})}{\lambda_m - 0.634 - 3(i/A)\exp(4.18(\frac{T - 303.15}{T}))} \quad (4)$$

By using the above equations, the voltage cell can be obtained:

$$V_{cell} = E_{cell} - a ln(\frac{i}{b}) - iRm - m\ln(\frac{1}{1-n}) \quad (5)$$

Where:

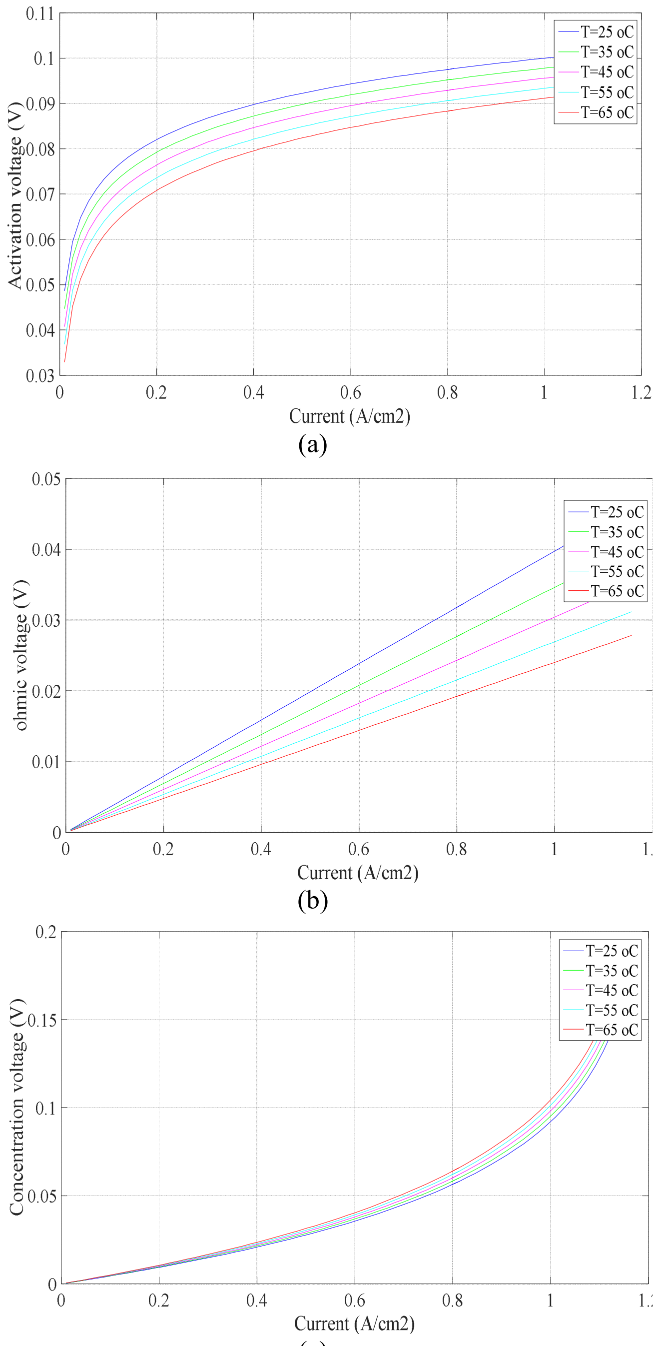
$$a = -2.3\frac{R.T}{\alpha F}\log(i_o)$$

$$b = 2.3\frac{R.T}{\alpha F}$$

$$m = \frac{R.T}{\alpha F}$$

$$n = \frac{i}{i_{\lim}}$$

Based on variation temperature, E_{cell}, a, b, R_m, m in (3-5) change with resulting changes in the activation, concentration and ohmic losses. Fig.1 shows that by increasing temperature, the activation, concentration and ohmic losses are also increased as well as the values of the polarization curve of the FC (see Fig. 2). A variation of the internal distribution of the temperature, also due to some internal faults, have a direct and quantifiable effect on the external FC cell or stack voltage, and this can lead up to just have temperature measurement avoiding the use of voltage measurements, or, in other words, the use of thermos-couples only can be used for diagnosis purposes.



(a)

(b)

(c)

Figure 1. Temperature effect on E, Vact, Vcon and ohmic losses.

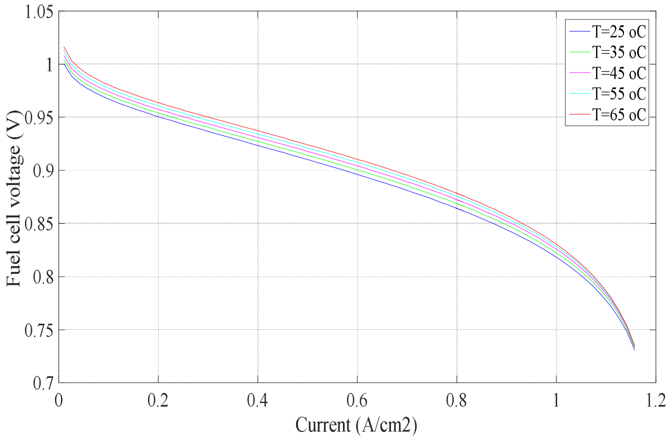
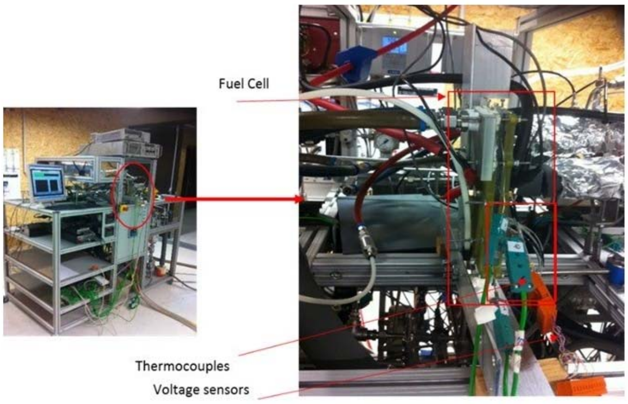


Figure 2. Temperature effect on polarization curve.

II. TEST BENCH EQUIPMENT

A suitable test bench has been realized in the Fuel Cell Laboratory (FCLAB) so that the variation of temperature and voltage under different current load profile can be verified experimentally (see Fig.3). In order to investigate the voltages and temperatures, the single cell of the PEMFC has been divided into three segments, in each of which thermocouples and voltage sensors have been installed (see Fig. 4). Data acquisition is controlled by software programs developed using LabVIEW. The sampling frequency was adjusted to 1 Hz in the control test panel. Current loads profiles are set constant between 0 and 55 A. In order to study variation temperatures, cooling air systems have been omitted in this test.

Figure 3. Test bench equipment from FCLAB



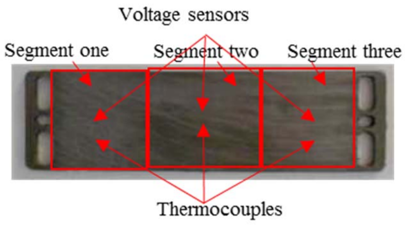


Figure 4. The single cell of the PEM FC.

The use of these low cost instruments results in this technique to be less expensive than other fault detection methods, like the cyclic voltammetry (CV), the current interrupt (CI) or the electrochemical impedance spectroscopy (EIS) [19-22].

III. RESULTS AND DISCUSSION

The voltage of each segment in the single cell has been recorded with voltage sensors installed between the bipolar plate and the cathode side. A typical cell produces the voltage from 0.6V to 0.7 V at full rated load. Voltage increased with temperature with higher voltage losses in the healthy mode of the FC. It should also be noted that in faulty mode such as drying and flooding increasing the temperature caused to be decreased voltage up to zero Volt [23-25].

As shown in Fig. 5 the voltage increases due to an increment in temperature. In particular, the voltage in the segment 2 has higher values than those of other segments. This might be explained by variation temperature due to inhomogeneous current density: actually, the current density in a FC does not flow homogeneously from the cathode to the anode side and can be distributed in different directions in the cell. This effect, however, is not considered in the model presented in this article and only the overall effect of temperature on voltage is considered. Fig. 6 shows the effect on temperature for current variations.

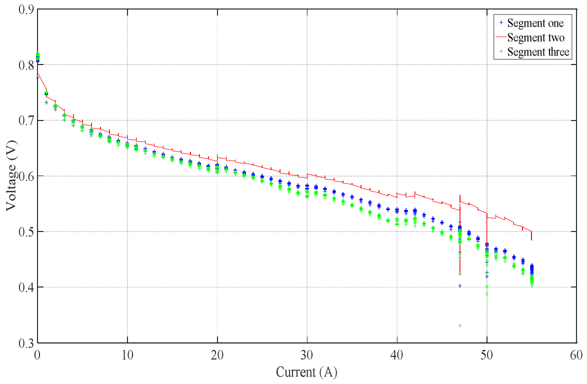


Figure 5. Voltage variations vs. current (experimental)

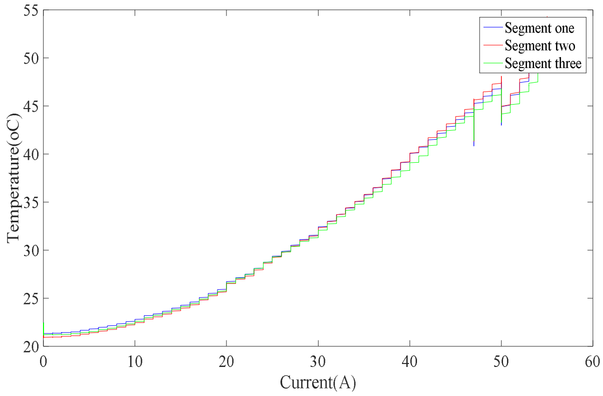
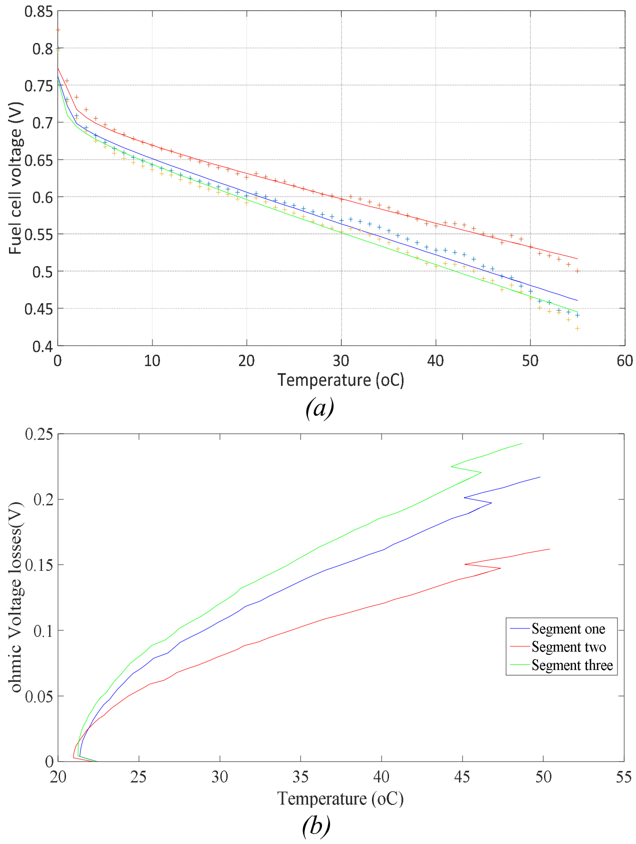


Figure 6. Temperature variations vs. current (experimental).

The polarization curve is made up of three regions: the activation zone, the ohmic zone and the concentration losses zone for different current load. In general, the activation losses zone is most affected at low current for decreasing cell voltage; in contrast, in high current density the concentration loss is the highest impact to voltage loss of the FC.

The test has been implement in single cell in order to show the impact of temperature variations on the voltage in the different segments of cell as shown in Fig.7.a. In this figure shows that the most voltage losses are linked to ohmic losses. Fig.7.b can be redrawn as in Fig.7.a to emphasis of ohmic losses vs temperature variations. This article is focused on variation of R_m due to variation of temperature and assuming constant values for the parameters a, b, m and n in the polarization curves. Indeed, the voltage differences in the segments of a single cell are related to ohmic losses zones (see Fig. 6b).



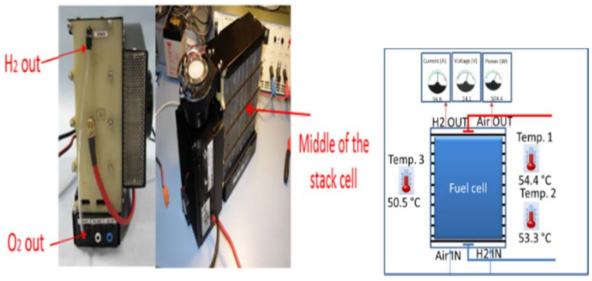
(a)

(b)

Figure 7. (a) FC voltage Vs Temperature (b) variation ohmic losses in different segments of single PEMFC.

IV. EFFECT OF THE TEMPERATURE ON VOLTAGE DISTRIBUTION IN THE STACK FUEL CELL

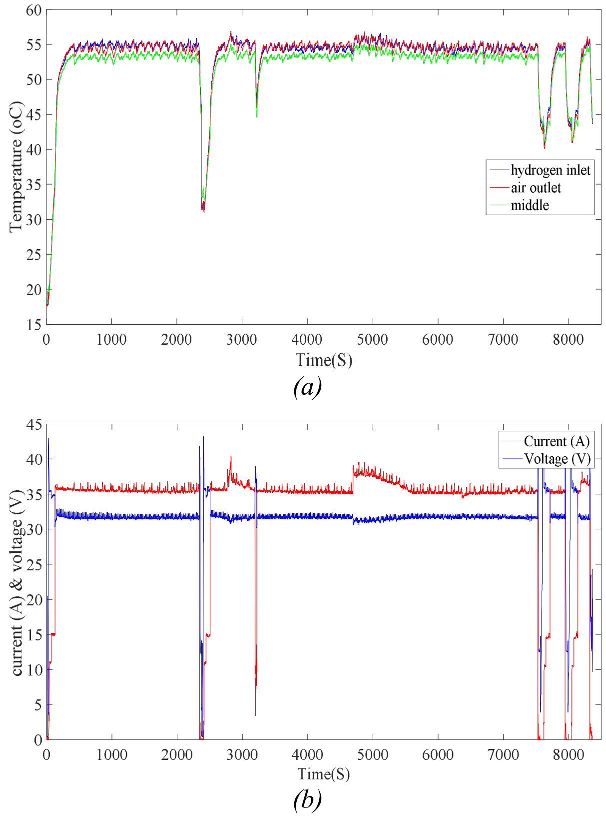
After testing and analyzing the temperature and voltage variations in the single cell, a PEMFC stack has been selected to verify the results in the stack. In order to control the accuracy of stack temperature measurements of the FC, three thermocouples have been installed in this system (see Fig. 8). Their positions have been chosen at critical points of the FC: the inlet of hydrogen, the outlet of oxygen and the middle of the near reaction air inlet channel.



(a) *(b)*

Figure 8. ***The stack PEMFC and its cooling system.***

As shown in Fig.9a, the temperature has different values along of the FC stack for example in the middle of the FC based on the position of the cooling system has the lowest values. In addition, the increase of the temperature in each step strongly depends on current load profile. The measurements of temperature and voltage have been performed by applying the current load profile shown in Fig.9.b shows the temperature measured in three zones of the stack (air outlet, middle of the near reaction air inlet channel, and hydrogen inlet) with red, green and blue curves respectively.



(a)

(b)

Figure 9. (a) Temperature measured in stack FC (b) profile of current and voltage stack PEMFC.

In this article, only the variations of ohmic losses due to variations of temperature have been considered on the FC voltage. As shown in Fig.10 the ohmic losses have low values compared to other segments due to the high temperature, which recorded in the middle of stack. This can be proved by equation 4 and 5.

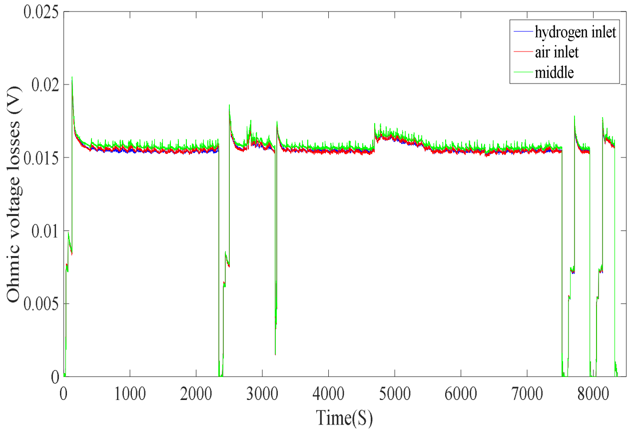


Figure 10. The ohmic losses calculation based on variation temperature.

Thus, the temperature distribution is directly related to voltages in single and stack fuel cell. This advantage can be used for fault diagnosis by omitting the voltage sensors.

V. CONCLUSIONS

This work presents the temperature distribution on the performance of the single and stack PEMFC for possible use in fault detection. In order to prove the direct relationship between temperature and voltage in the single and stack of a FC, two experimental tests have been carried out. In the first, the performance of the single cell based on the voltage and temperature distribution has been validated. In the second the voltage and temperature distributions have been tested in the stack PEMFC. A fault detection of the FC can be therefore simplified by measuring only the temperature in the stack FC with resulting reduced cost since only thermocouples are used for fault detection. The advantage of this technique is that the voltage sensors for fault diagnosis can be omitted. The fault detection of fuel cell can be therefore simplified by applying this technique and the costs reduced.

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