DYNAMIC MODEL USED TO INVESTIGATE THE INFLUENCE OF OPERATING CONDITIONS ON THE BEHAVIOR OF COMMERCIAL PEMFC

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Numerical modeling plays an important role in the development and the improvement of fuel cells. This paper presents a model which is used to analyze and to understand the behavior of a commercial Proton Exchange Membrane Fuel Cell (PEMFC) under variable operating conditions. These working conditions will also be investigated by means of properly designed experimental tests, which involve different electrical polarization situations.

The study of fuel cell behavior in transient conditions gives information and suggests strategies for fuel cell optimization. Nowadays many numerical models are available to describe steady state behavior but models capable of predicting transient phenomena are very few. The dynamic model discussed in this paper is used to investigate the cell behavior (voltage variations over current density, i.e. dynamic polarization curves) for different cell temperature, species stoichiometry, species inlet temperature and humidity.

Experimental tests will consist in the study of the dynamic polarization curve which gives information on fuel cell behavior at different operating conditions. The main factors affecting the performance of a commercial fuel cell will be analyzed. The design of experiments (DOE) technique will lead us to the development of some regression models which can accurately reproduce the influence of each parameter over the fuel cell voltage and consequently to estimate the combined effects.

The regression models can also be used to check the results of the numerical models. Numerical modeling is essential in order to reduce the experimental time required to predict a complex system behavior in unsteady operating conditions and hence to reduce the economical impact of such investigation in the industrial context.

In the present paper, the numerical simulation results are compared with those due to the experimental results and the main conclusions are pointed out.

Keywords: PEM fuel cell, mathematical modeling, ANOVA

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Table 1

Nomenclature	
PEMFC	Polymer Electrolyte Fuel Cell
FC	Fuel Cell
MEA	Membrane Electrode Assembly
$p_{air/oxygen}$	Pressure of air/oxygen
$T_{air/oxygen}$	Temperature of air/oxygen
$\Phi_{air/oxygen}$	Humidity of air/oxygen
$P_{hydrogen}$	Pressure of hydrogen
$T_{hydrogen}$	Temperature of hydrogen
$\Phi_{hydrogen}$	Humidity of hydrogen
DOE	Design Of Experiment
ANOVA	Analysis Of Variance

1. Introduction

Hydrogen and electricity, two words that putted together could represent the future to a cleaner world. Nowadays the hydrogen seems like it is going to be the promising vector for obtaining sustainable energy, while fuel cells represent the most efficient conversion devices which “transforms” hydrogen obtained from different sources into energy. A fuel cell is an electrochemical energy conversion device that uses fuel and oxidizer to produce electricity and water [1]. A Fuel cell comprises: an electrolyte membrane (usually Nafion™) surrounded on each side by an electrode membrane (this is called MEA-membrane electrolyte assembly) the catalyst, the gas diffusion layer the gas channels (hydrogen at the anode side and oxygen at the cathode side).

Proton exchange (or polymer electrolyte) membrane fuel cell (PEMFC) is considered as being one of the most promising technologies able to produce efficient and environmentally friendly energy for various applications. More and more attention is paid to PEMFC for powering electric vehicles especially because of its low temperature operation and its high power density [2]. Due to its characteristics presented above a PEM fuel cell is perfectly suitable for stationary isolated house that can be heated and powered with the help of a PEM fuel cell and also for non stationary applications such as laptop and mobile phone power source.

The experimental part of the paper has been conducted in HySyLab, a research centre in Turin, Italy. The fuel cell analyzed was an “Electrochem” fuel cell equipped with a highly efficient “Gore™” MEA.

In literature, the papers applying the technique of parameter estimation are not so many. Usually, parametric models are developed with empirical modeling techniques and equations. In some cases, as well as in the presented paper can be found, the developed model is validated through a lot of experimental activity, allowing this way to determine some model parameters [3]. In the present paper a number of 16 sets of experiments have been performed in order to find the model parameters. The parameters analyzed were: temperature of the cell, inlet pressure of reactants and humidity of reactants. The aim of every research made in this area is to ensure for the FC proper and optimal operating conditions, thus leading to high power or efficiency delivery. To do so it is not easy mainly because of the high number of parameters that needs to be controlled: FC temperature, gas pressure, gas flow, relative humidity of hydrogen and air, polarization curve profile, etc. All these parameters put together have strong impacts on the FC performance and they relate among themselves by nonlinear relations, difficult to be modeled [4]. Usually, a large number of experimental tests are often needed to correctly analyze the performances of a given FC system or to identify the parameters of a physical model. The design of experiment (DOE) method is used in order to evaluate the respective impacts of the physical controlled parameters on the FC operation. This methodology is used by chemists [5] in order to characterize the fuel cell and its materials, to determine the most significant parameters, or to highlight the possible correlations between these ones [4]. During tests we always had in mind two objectives: to obtain the maximum of the power produced by the fuel cell and to reach the maximum of the fuel cell efficiency for given ranges of air/hydrogen flows and pressures.

2. Experimental stand and procedures involved

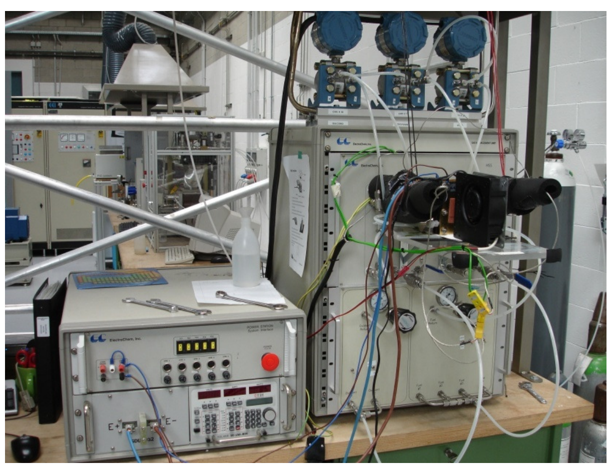


Figure 1. Experimental stand in HySyLab, Torino, Italy

The experimental activity plays a very important role in the research activity and also represents the basis of the majority of the published papers. When analyzed, a FC provides information about its performances and status with respect to the polarization curve. If the paper studies the influence of variation of working parameters such as temperature, stoichiometry, pressure of reactants, humidity, quality of the polymeric membrane on FC's performance, all these are translated in the polarization curve. Making the FC operating at different values for the factors stated above and not only has been studied in many papers [3][6]. In [3], an experimental analysis of the effects of the stack operation independent variables on the cogenerative performance of a PEMFC stack has been analyzed. With the help of the statistical methodology (used for the experimental data analysis) was the factorial design. The authors analyzed in the paper the significance of some variables such as anode and cathode flow dew point temperature and cathode flow stoichiometry considering their single and combined effects on the electric and thermal power using the above stated method. Also in [6] the authors analyzed and thoroughly described the effects that cell temperature, anode flow temperature in saturation and dry conditions, cathode flow temperature in saturation and dry conditions and reactants pressure have over the PEM fuel cell performance.

2.1. Aims of the paper

The aim of the paper is to experimentally analyze using the statistical method, the combined effects of the working parameters on the performance of the PEM fuel cell. As these authors stated above analyzed in their papers the present article uses the factorial design combined with the experimental session in order to observe and characterize the influence that reactants temperature, humidity and stoichiometry has over the polarization curve of the fuel cell (current reported to voltage) thus offering a good opportunity to improve cell performance.

The fuel cell involved in the experiment has a 25 cm^2 of active area and it is made by "Gore™", a world famous MEA producer. The experiment methodology consisted in varying the studied parameters in the same time and this way having the possibility to observe the FC behavior.

As it can be seen in Figure 1, the experimental stand consists of a FC, pressure and temperature regulators for inlet and outlet reactants (i.e. hydrogen and oxygen), probes for accurate measurements and software for control and display of the main parameters that were analyzed.

3. Results and discussion

The FC temperature, humidity and pressure of reactants have a decisive influence over its performance and lifetime and knowing the converse influence of these factors is decisive. In the present paper a full factorial design has been done: an output variable (such as voltage) can be correlated with the input variables (temperature, humidity and pressure) pointing out their effects. Once we choose the *n* input factors the next step is to choose the range of their variation (i.e. the experimental range of variation). Due to the fact that the experiments done in this paper were made at the lower and the upper bound of the variation range (see Table 2), a number of 2^n experiments are required. To have a better accuracy we choose to replicate these experiments. If each combination of these factors analyzed is replicated then an ANOVA can be performed. The data evaluation has been made at three different values of current densities: 0.6 A/cm^2, 1.2 A/cm^2 and 2 A/cm^2.

Each factor analyzed is labelled with a capital letter and to describe the influence that they have on each other a lowercase letter are used. To analyze the effects of the studied factors we have used the Yates technique. To use this technique, the factors influence combination is written in a dedicated form [7 , 8]. The values for the parameters that were used are shown in Table 2. Note that the stoichiometry for the reactants has been kept at a value of 1.5 for hydrogen and 2.5 for air during all the time.

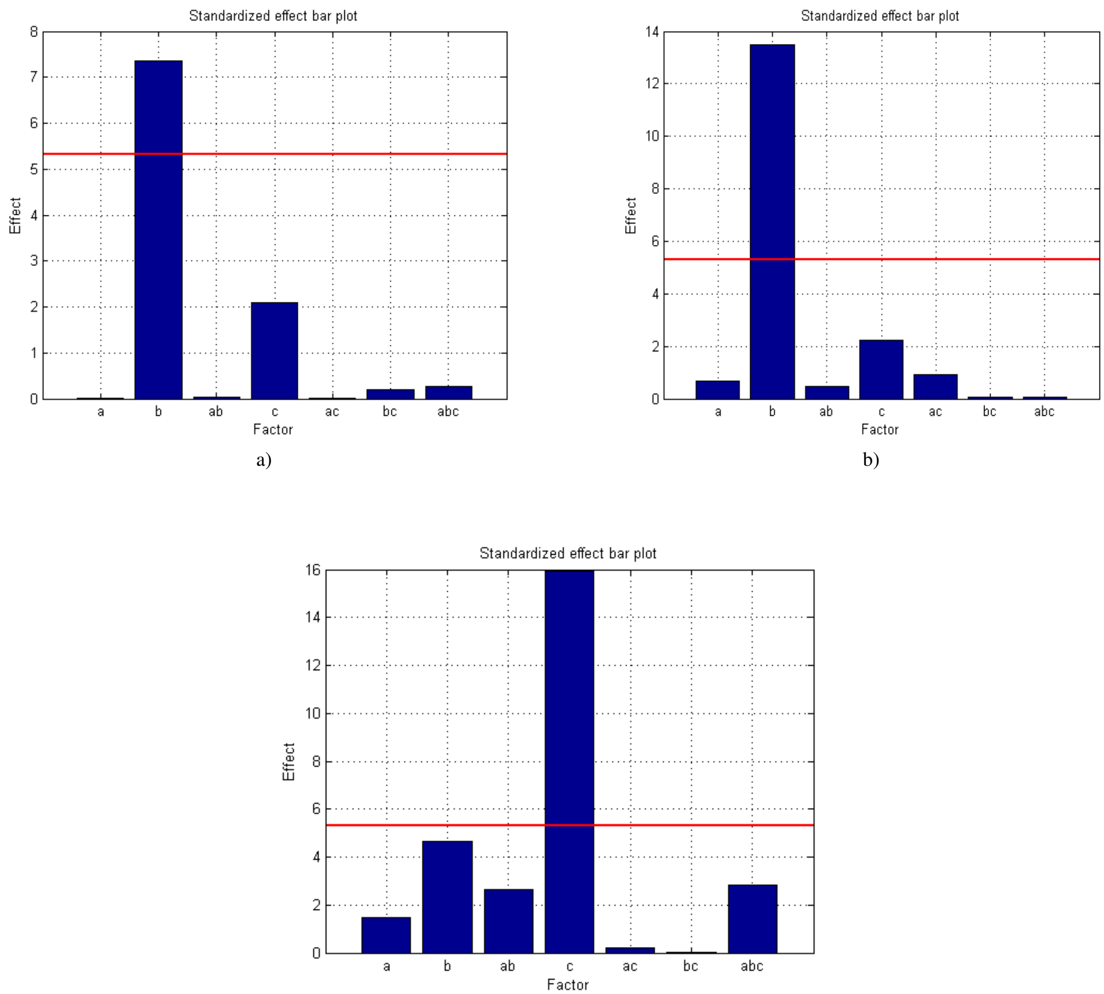
Table 2

Analyzed factors				
Factor	Description	Minor level of analysis	Major level of analysis	Description
A	T_{cell}	70^0C	80^0C	Temperature of the FC
B	$p_{H2,oxygen}$	1 (atmospheric pressure)	1.5 bar	Pressure of the reactants (air and hydrogen)
C	$\varphi_{reactants}$	50%	100%	Humidity of reactants (air and hydrogen)

Due to the fact that in this paper a number of 3 factors have been chosen a number of 2^3X2=16 experiments are needed. The complete regression equation is shown below (only for 0.6A/cm^2 current density):

Voltage=+2.28-0.0262*a-0.0225*b-1.037*ab+0.00034*c+0.0156*ac+0.0143*bc-0.0002*abc (1)

From the graph presented in Figure 2 we can observe the effects that each factor analyzed has. The graphs indicate the influence of the factors at 0.6 A/cm^2, 1.2 A/cm^2 and 2 A/cm^2 current densities.



c)

Figure 2) Combined factor's effect for a value for current density of: a) 0.6 A/cm^2; b) 1.2 A/cm^2; c) 2 A/cm^2.

As it can be seen, at lower current densities the inlet pressures of the reactants have a greater influence. For the first current densities that were considered, the influence of the pressure is significant. But at a greater value for the current density we can observe that the humidity of the gases has a significant greater effect. Also the combined effects of the analyzed factors are more obvious when the current density increases. For a better understanding of the influence that the factors have over the voltage (analyzed dependent variable) and based on the regression models, a plot of these factors is presented below in Figure 3.

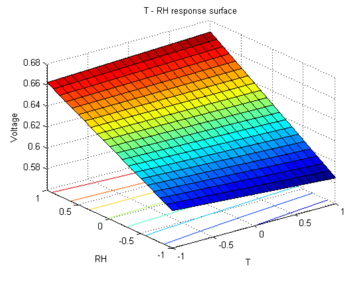
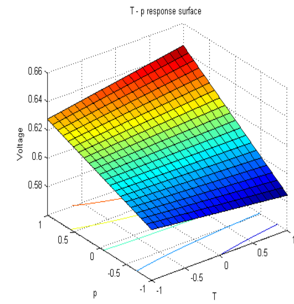
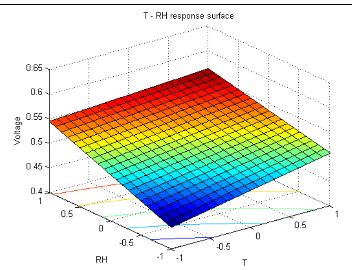
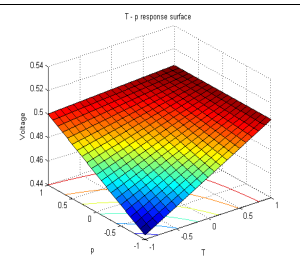
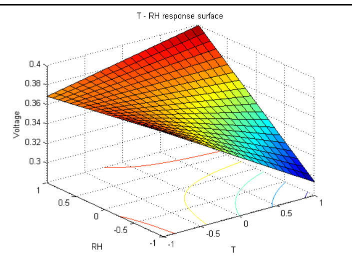
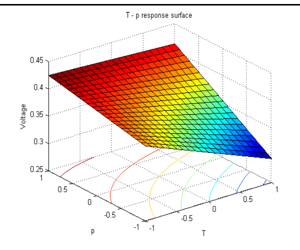
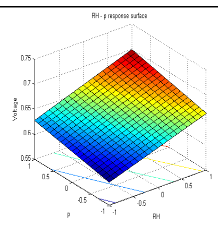
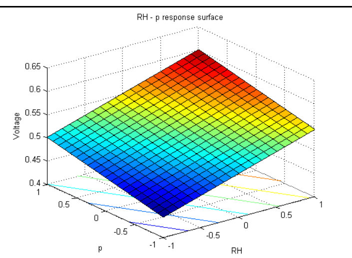
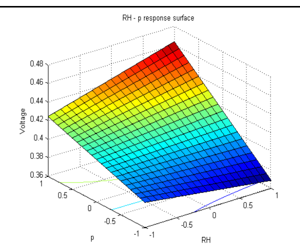
Factors	Current density [A/cm^2]	Response surface	
A	0.6		
	1.2		
	2		
B factor influence			
Current density [A/cm^2]	0.6	1.2	2
			

Figure 3). Contour plots of the dependent variable (voltage) as a function of the analyzed factors

3. Conclusions

In the paper, the experimental analysis, using a statistical methodology of the single and combined effects for the main operation independent variables (cell temperature, humidity of reactants and inlet pressure of reactants), on the FC performance (Voltage) has been performed.

Shortly, the main conclusions that can be obtained are presented below.

If considered, the combined effects of humidity and operating pressure have a greater impact than each factor apart. At greater values for pressure and humidity a certain improvement of FC behaviour could be observed.

The anode and cathode inlet temperature have a certain influence on FC behaviour.

The factorial design is a very important method used to analyze the significance of the variation of the main working parameters of the FC.

The stoichiometry plays an impotent role but it has not been analyzed in this paper.

An increase of the cell temperature has a well defined positive effect on FC performance especially if the humidification of the membrane is sufficient. It has been noted that when the temperature increases, the membrane conductivity and the exchange current density also increase.

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