Available at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/he

Temperature control of a PEM fuel cell test bench for experimental MEA assessment

J.J. Moré [a,b,*], *P.F. Puleston* [a,b], *C. Kunusch* [a,b], *A. Visintin* [b,c]

[a] *LEICI, Departamento de Electrotecnia, Universidad Nacional de La Plata (UNLP), calle 1 esq. 47 s/n, 1900 La Plata, Argentina*
[b] *Consejo de Investigaciones Científicas y Técnicas (CONICET), Av. Rivadavia, No 1917, C1033AAJ, Ciudad Autónoma de Buenos Aires, Argentina*
[c] *Instituto de Investigaciones Físico-Químicas Teóricas y Aplicadas (INIFTA), Diag. 113 y 64 s/n, 1900, La Plata, Argentina*

ARTICLE INFO

Article history:
Received 3 December 2009
Accepted 17 December 2009
Available online 29 January 2010

Keywords:
Fuel cell
Temperature control
Thermal model

ABSTRACT

This paper presents the design, implementation and testing of a temperature control for a laboratory PEM fuel cell stack work bench intended for evaluation of experimental MEAs. The controller design is based on a thermal model of the fuel cell stack developed by the authors. The model is extended to the complete temperature range by considering a nonlinear description of the heating resistances. Its parameters are experimentally adjusted and its accuracy is validated in all the temperature operating range. Then, the temperature control is developed, using a proportional-integral structure with anti-windup features. It is implemented in a PC connected to an *ad-hoc* equipment of acquisition and control, that drives distributed cycles actuators to energize two heating resistances. The controller proved to be capable of regulating the stack temperature in a wide operating range, while eliminating the ripple typical of ON-OFF actuators. Finally, experimental results of closed loop operation are presented, demonstrating the good performance of the proposed control set up and thermal model.

1. Introduction

The principle of operation of the fuel cells was discovered more than a century ago. However, only in recent years technological advances and continuous research in this area has led to significant results. Among the most important, is possible to remark the cost reduction and flexibility increase of this technology [1].

Fuel cells are a fundamental piece to reduce the use of fossil fuels [2], being a clean technology that consume hydrogen to produce electricity, together with water and heat as sub-products. Particularly, the Polymer Electrolyte Membrane (PEM) fuel cells are among those that have shown great progress for their use in practical applications, such as automotive industry [3] and the hybrid systems for electrical energy generation [4,5].

In this context, a great number of articles in this area have been published. Many of them, with the objective of study and model the behavior of fuel cell systems. Though, simple practical and efficient thermal control models are not common in literature. Also, most of the models that arise from this works do not consider temperature dynamics or are not oriented to temperature control design [6–8].

With this motivation is that in the present work the temperature control problem of a laboratory PEM fuel cell stack test bench for experimental membrane-electrode

* *Corresponding author at*: LEICI, Departamento de Electrotecnia, Universidad Nacional de La Plata, calle 1 esq. 47 s/n, 1900 La Plata, Argentina. Tel./fax: +54 221 4259306.
E-mail address: jmore@ing.unlp.edu.ar (J.J. Moré).
0360-3199/$ – see front matter
doi:10.1016/j.ijhydene.2009.12.095

assemblies (MEAs) evaluation is considered. It is important to stress that due to the requirements and specifications of the tests, a versatile and efficient temperature regulation is needed, to ensure adequate membrane and catalysts assessment. For the design and evaluation of the controller a slightly nonlinear thermal model of the plant is proposed, based on the linear model structure developed by the authors in [9]. This improved model is fitted for a better representation of the plant.

The present article is organized as follows. In section 2 the experimental fuel cell characteristics, together with the laboratory equipments and instrumentation available for the temperature control implementation are detailed. Section 3 focuses on the fuel cell stack thermal model. The basic linear structure and the improved model are presented and their performances are assessed through simulations and experimental tests. Section 4 deals with the design and implementation of the controller. Section 5 presents experimental results obtained from the tests of the controller. Additionally, comparisons with the simulation results using the proposed model are shown. Finally, in Section 6, conclusions are given.

2. Equipment and instrumentation

The laboratory PEM fuel cell stack test bench considered in this work mainly comprises an experimental 6-cell PEM fuel cell stack, an acquisition and control (A&C) equipment, a dedicated PC, hydrogen and oxygen bottles to feed the stack, two humidifiers and several valves and pressure gauges. The stack and most of the associate subsystems were designed and developed in the INIFTA [10], with the main objective of assessing novel MEAs. The particular MEAs under consideration for the experimental results of this paper are based on a commercial 120 μm thick *Nafion*® 115 membrane. The active area of each cell is of about 9 cm^2. The gas diffusion layers are built of 250 μm thick carbon fiber. The bipolar plates are made of graphite and their measures are 8 cm side and 6 mm thick. At each extreme of the stack, a 1 cm thick steel plate is placed. Synthetic gaskets of 250 μm thick, based on silicone and glass fiber, are used as sealing elements between the bipolar plates and the membranes (Fig. 1).

The heating actuator has been adapted to be capable of quasi-proportional power delivery. It consists of two 150 W heating resistances embedded in the steel plates, connected to a distributed cycle circuit [9]. Then, the heating power (P_H) delivered by the actuator is not always maximum, but quasi-proportional:

$$P_H = P_R \cdot \delta \tag{1}$$

where P_R is the maximum heating resistance power and $0 \le \delta \le 1$ is a duty cycle, proportional to a 6 bits digital control input. So, with this configuration is possible to deliver 64 levels of heating power. Unlike ON-OFF actuators, this particular set-up, properly controlled, is capable to reduce the temperature ripple to negligible values.

The temperature profile of the stack is measured with 3 sensors: two semiconductor temperature sensors (TMP35D), at each extreme of the stack, and a thermocouple (*K* type), in the center (Fig. 1).

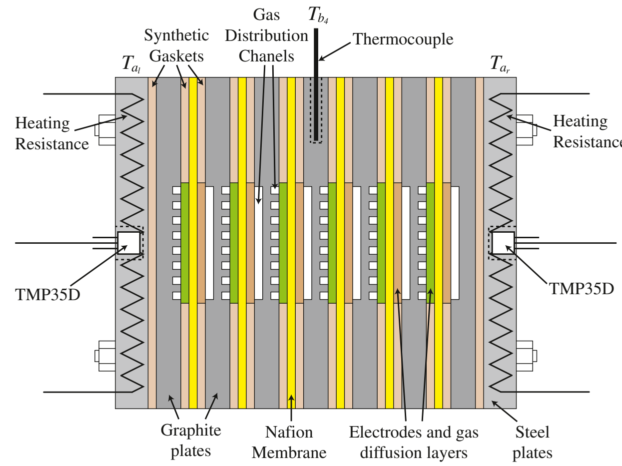


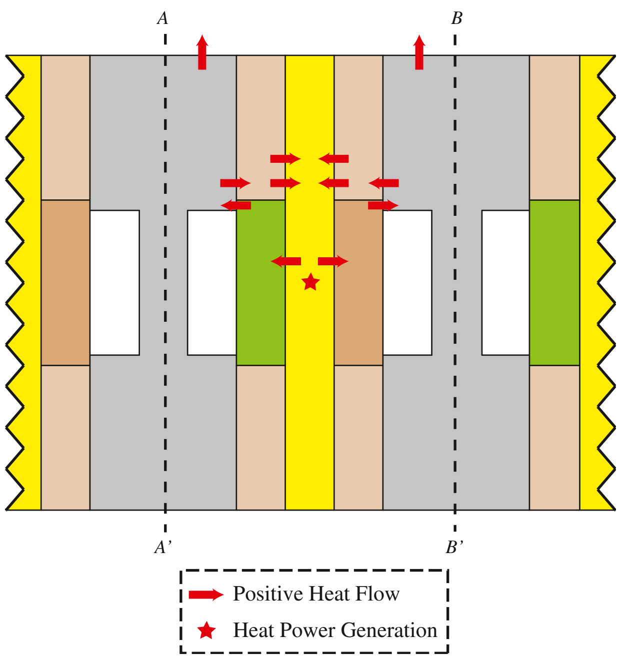
Fig. 1 – Schematic view of the fuel cell stack for experimental test developed at the *INIFTA*.

Both, the actuator and the temperature sensors, are connected to the A&C equipment, specially designed for the laboratory fuel cell stack work bench. The equipment is attached to the PC through an RS-232 port. In this way, it is possible to modify set-points of different controlled variables and visualize on screen the stack voltage, current, stack and ambient temperatures among other variables. Besides, it has several input and output ports, including the digital outputs required to provide the computed control action to the heating actuator inputs.

3. Thermal model

The controller design is based on a thermal state model of the stack, obtained through a modular approach developed by the authors [9]. The proposed basic module for a single cell is schematically presented in Fig. 2. In Fig. 2a is presented within dotted lines the section considered for modelling and the main heat flows. Fig. 2b presents the electric equivalent circuit of the single cell thermal model, where T_{b_i} and $T_{b_{i+1}}$ are the *i*-th and (*i* + 1)-th bipolar plate temperature; T_{m_i} is the *i*-th membrane temperature; R_i is the lumped thermal resistance of the *i*-th bipolar plate, membrane and electrode; $R_{amb_{i+1}}$ is the lumped thermal resistance of the (i + 1)-th bipolar plate to ambient; $C_{b_{i+1}}$ is the thermal capacitance of the (i + 1)-th bipolar plate and P_{m_i} is the heat power generated in the *i*-th membrane. Applying this thermal model to the fuel cell stack under study, the resultant model is linear, symmetric and consists of nine states and two control inputs.

The next step to obtain a thermal model, suitable for analysis and design, is to readjust the theoretical values of the parameters in accordance with experimental data. To this end, open loop fitting tests are conducted, applying appropriate heating power steps to the plant. After a fitting procedure, the following nine order model for the fuel cell stack is obtained:



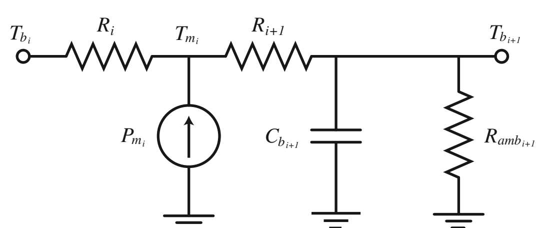


Fig. 2 – Single cell modular model.

$$\dot{x} = A\cdot x + B\cdot u + B_d\cdot u_d \tag{2}$$

$$A = 10^{-2}\begin{bmatrix} -1.328 & 1.2959 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 13.5105 & -17.6102 & 4.0326 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 4.0876 & -8.2432 & 4.0876 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 4.0876 & -8.2432 & 4.0876 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 4.0876 & -8.2432 & 4.0876 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 4.0876 & -8.2432 & 4.0876 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 4.0876 & -8.2432 & 4.0876 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 4.0326 & -17.6102 & 13.5105 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1.2959 & -1.328 \end{bmatrix} \tag{3}$$

$$B = 10^{-3}\begin{bmatrix} 1.778 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 1.7778 \end{bmatrix} \tag{4}$$

$$B_d = 10^{-3}\begin{bmatrix} 0.3203 & 0 \\ 0.6715 & 9.2669 \\ 0.6806 & 18.7867 \\ 0.6806 & 18.7867 \\ 0.6806 & 18.7867 \\ 0.6806 & 18.7867 \\ 0.6806 & 18.7867 \\ 0.6715 & 9.2669 \\ 0.3203 & 0 \end{bmatrix} \tag{5}$$

where the system state (x), control input (u) and perturbation input (u_d) vectors are:

$$x = \begin{bmatrix} T_{a_l} \\ T_{b_1} \\ T_{b_2} \\ T_{b_3} \\ T_{b_4} \\ T_{b_5} \\ T_{b_6} \\ T_{b_7} \\ T_{a_r} \end{bmatrix}; u = \begin{bmatrix} P_{H_l} \\ P_{H_r} \end{bmatrix}; u_d = \begin{bmatrix} T_{amb} \\ P_m \end{bmatrix} \tag{6}$$

with T_{a_l} and T_{a_r} the steel plates left and right temperatures, respectively; T_{b_j} the j-th bipolar plate temperature. P_{H_l} and P_{H_r} are the heating powers (see (1)) delivered by the left and right resistances, respectively; T_{amb} is the ambient temperature and P_m is the calorific power generated per membrane, due to the chemical reaction and the proton flow. Simulation and experimental results are compared in Fig. 3. It can be observed that a good characterization of the thermal behavior is attain with the proposed model. Nevertheless, given that the parameters fitting was focused on the working temperature range of the stack, the linear model better represents the plant in the range from 60 °C to 70 °C.

However, with a slight modification to the model structure, it is possible to improve its accuracy in an extended temperature range. This can be achieved by considering a nonlinear variation of the maximum heating resistance power with the temperature. This translates into a variation of the thermal power delivered to the stack, in accordance with (1). Therefore, the following second order polinomial is used to approximate the dependence of P_R with temperature:

$$P_{R_i}(T_i) = P_{R_N}\cdot\left(a_2\cdot T_i^2 + a_1\cdot T_i + a_0\right) \tag{7}$$

where P_{R_N} is the nominal maximum power of the heating resistances and T_i stands for T_{a_l} or T_{a_r}, depending on the left or right resistance is considered. The best fitting polinomial coefficients are:

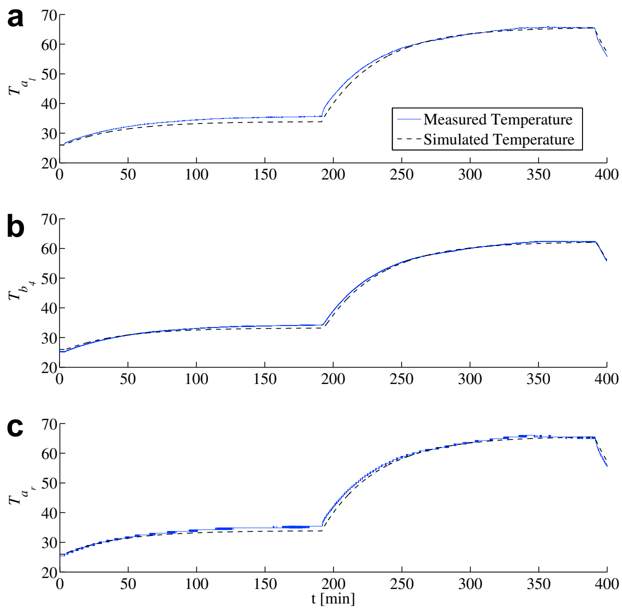


Fig. 3 – Open loop measured and simulated temperatures of the stack with the proposed model.

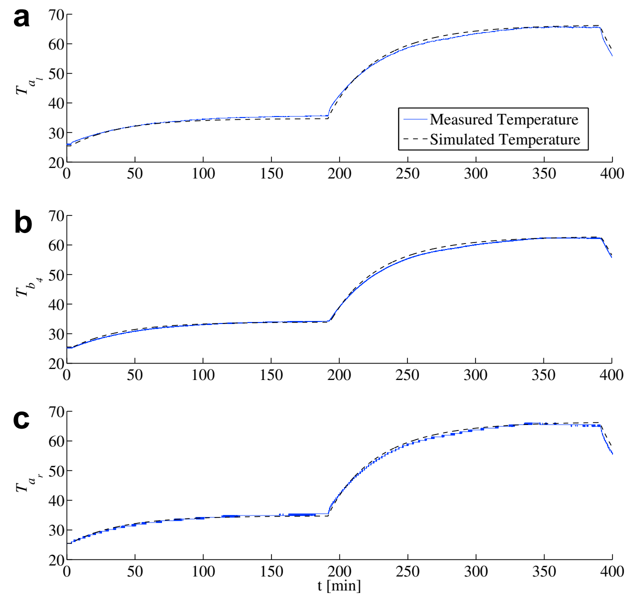


Fig. 4 – Open loop measured and simulated temperatures of the stack with the improved model.

$$a_2 = 1.1e^{-4}; a_1 = -0.0144; a_0 = 1.4562 \tag{8}$$

In Fig. 4, open loop responses of the system and the model improved with the nonlinear power (7) are presented. It can be appreciated the very good matching of the improved model to the experimental data in a broader temperature range, including transient and steady state.

4. Controller development

The main control objective for this particular application is guaranty different regulation points of the stack central temperature within an error of 1%. Experimental analysis has established that such regulation ensures an adequate operation temperature profile along the fuel cell stack. Looking for the most simple suitable control implementation to attain this objective, the heating resistances are controlled in unison, that is the control algorithm generates a single duty cycle δ (see (1)) to command both distributed cycles heating actuators. In this way, a Single Input/Single Output (SISO) control problem is posed and a proportional-integral controller with anti-windup features is proposed as a practical solution. Then, the following digital algorithm is implemented in the PC:

$$u[k] = u_P[k] + u_I[k] + u_D[k] \tag{9}$$

where u_P, u_I and u_D are the proportional, integral (anti-windup) and derivative (filtered) sub-control actions, respectively. Their definitions are as follows:

$$u_P[k] = K_P \cdot e[k] \tag{10}$$

$$u_I[k] = u_I[k-1] + K_I \cdot T_s \cdot f_{ARW}(e[k], u[k]) \tag{11}$$

$$u_D[k] = \frac{(2 \cdot T_d - T_s)}{(2 \cdot T_d + T_s)} \cdot u_D[k-1] + \frac{2 \cdot T_s}{(2 \cdot T_d + T_s)} \cdot K_D \cdot e_D[k] \tag{12}$$

$$e_D[k] = \frac{1}{T_s} \cdot (e[k] - e[k-1]) \tag{13}$$

with K_P, K_I and K_D the proportional, integral and derivative gains; $e[k]$ the k-th temperature error, defined as

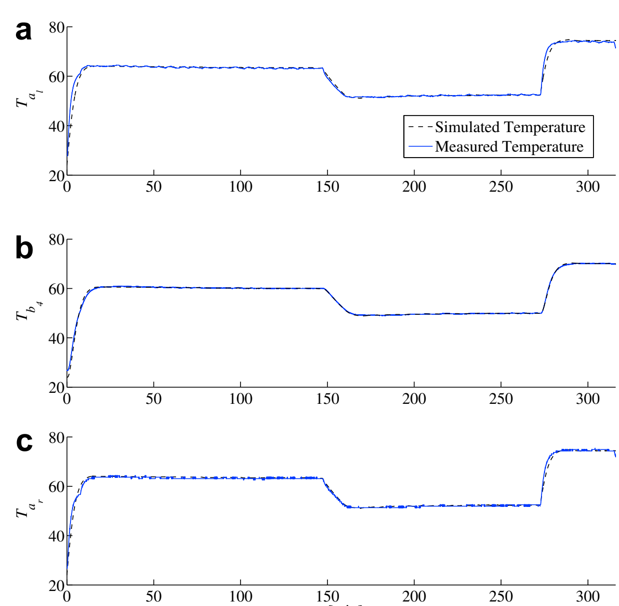


Fig. 5 – Measured and simulated temperatures of the controlled system.

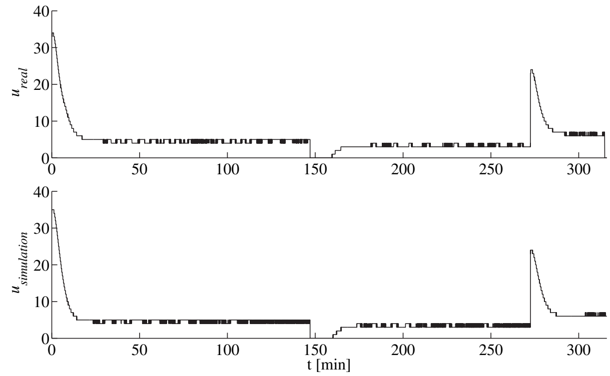


Fig. 6 – Real and simulated control actions.

$e[k] = T_{ref}[k] - T_{b_4}[k]$, being T_{ref} the reference temperature. T_s is the sampling period in seconds; T_d is a parameter to adjust the derivative filter bandwidth and f_{ARW} is an anti reset windup function:

$$f_{ARW}(e[k], u[k]) = \begin{cases} e[k] & 0 \le u[k] \le 63 \\ 0 & u[k] < 0 \vee u[k] > 63 \end{cases} \quad (14)$$

The control specifications for the laboratory PEM fuel cell under consideration in this case of study are as follows: maximum temperature overshoot equal to 1 °C; regulation error less than 1% and setting time of 10% less than $0.4 \cdot \tau^*$, with τ^* the dominant open loop time constant in the operation range ($\tau^* \cong 40$ min). Therefore, the controller has been tuned and validated using the proposed thermal model. The simplest set of parameters that meet the specifications are: $K_P = 1$, $K_I = 0.0006$ and $K_D = 0$, while the sampling period has been selected $T_s \le 0.001 \cdot \tau^*$ ($T_s = 1$ s in this application). Note that the experimental control set-up allows to easily modify the controller parameters and reference, facilitating the assessment and contrasting of different control tunings.

5. Experimental results

This section presents the experimental results of the temperature control system operation. The configured control loop is evaluated by applying a series of temperature reference steps and the controller design method is validated through comparisons with the experimental data.

Fig. 5 depicts the experimental and simulation results. It can be observed the closed loop temperature evolution, using a reference step of 60 °C. When steady state is reached, the system has a negligible limit cycle with an amplitude of 0.1 °C, approximately. Close to the 150 min the reference is changed to 50 °C, and at t≅270 min, an increment of 20 °C is introduced. In both cases a very good temperature regulation is observed.

It can be also appreciated the accurate performance of the simulated model in closed loop, whose response closely matches the experimental data. In Fig. 6, a comparison between the real control action and the simulated one is shown. It can be appreciated a great deal of correlation between them, supporting the validity of the proposed model.

6. Conclusions

The current work presented the development, implementation and assessment of a temperature control system for a laboratory PEM fuel cell stack test bench, intended for catalysts, electrodes and membrane evaluation. To this end, a modular thermal model of the stack was proposed. The model was adjusted through experimental data and improved considering a nonlinear description for the heating resistances. Thus, the model accuracy was extended to a broader range, covering temperatures from 20 °C to 80 °C. A proportional-integral controller with anti-windup features was designed and successfully implemented. Very good simulation and experimental closed loop results were obtained. They proved the suitability of this control set-up for this application and the adequacy of the proposed thermal model for the control design and system analysis. Particularly, the experimental results showed that an error close to ± 0.2% was attained, while the overshoot was less than 1 °C, fulfilling the thermal specifications of the laboratory PEM fuel cell stack work bench.

The control system set-up shows to be versatile and proficient for the task. It can be mentioned that in the case that extra computational power is required, one of the microcontrollers available in the A&C equipment can be dedicated to perform the control calculations.

Acknowledgements

This work was supported by the UNLP, CONICET and Secretaría de Ciencia y Técnica (SECyT), Argentina. The authors want to thank the INIFTA, specially Dr. W. Triaca and Ing. C. Tori for their support and good disposition, and also Ing. A. Zumarraga for his significant collaboration.

REFERENCES

[1] Larminie J, Dicks A. Fuel cell systems explained. 2nd ed. John Wiley & Sons Inc; 2003.

[2] Anahara R, Yokokawa S, Sakurai M. Present status and prospects for fuel cell power systems. Proc IEEE 1993;81: 399–408.

[3] Adams J, Yang W.C., Oglesby K, Osborne K. The development of ford's p2000 fuel cell vehicle, SAE Paper 2000-01-1061.

[4] Onar O, Uzunoglu M, Alam M. Dynamic modeling, design and simulation of a wind/fuel cell/ultra-capacitor-based hybrid power generation system. Journal of Power Sources 2006;161: 707–22.

[5] Uzunoglu M, Alam M. Dynamic modeling, design and simulation of a combined pem fuel cell and ultracapacitor system for stand-alone residential applications. IEEE Transactions on Energy Conversion 2006;21(3):767–75.

[6] Pukrushpan J, Stefanopoulou A, Peng H. Control of fuel cell power systems. London: Springer; 2004.

[7] Hatziadoniu C, Lobo A, Pourboghrat F, Daneshdoost M. A simplified dynamic model of grid-connected fuel-cell generators. IEEE Transactions on Power Delivery 2002;17(2): 467–73.
[8] Nguyen T, White RE. A water and heat management model for proton-exchange-membrane fuel cells. Journal of Electrochemical Society 1993;140(8):2178–86.
[9] Moré J, Kunusch C, Puleston P, T. C. Instrumentación y modelado térmico de una pila de combustible pem. XXIº Congreso De Control Automático, AADECA 2008.
[10] Tori C.A, Visintin A, Triaca W.E. Comportamiento en operación de una celda de combustible, unitaria, de tecnología pem de hidrógeno y oxígeno, Primer Congreso de Hidrógeno y Fuentes Sustentables de Energía (HYFUSEN).