Evaluation and simulation of a commercial 100 W Polymer Electrolyte Membrane Fuel Cell (PEMFC) Stack

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Abstract: - In this study the performance of a commercial air-breathing 100 W Polymer Electrolyte Membrane Fuel Cell (PEMFC) stack is experimentally and theoretically evaluated using a widely known commercially available generic mathematical model of the Transient System Simulation Software (TRNSYS). The simulation results were compared with the experimental data to investigate the convergence between them and to validate the model in order of establishing confidence in the model when used with rather small FC stacks. The PEMFC stack used in this project is a commercial product named'H-100FC'. The conclusions coming out of this study show that the simulation results are in good agreement with the experimental data and consequently this model can be reliably used to simulate sub kilowatt PEMFC's. A series of interventions for the improvement of the performance of this commercial PEMFC stack is proposed.

Key-Words: - **PEMFC; Fuel Cell; Experimental; Commercial; Sub-kilowatt; Simulation; TRNSYS**

1 Introduction

1.1 Historical background

Fuel cells have been used in a great number of applications since 1839 where the first fuel cell was developed by Sir William Robert Grove. The first complete fuel cell system was developed at 1932 by Dr. Francis T. Bacon with a power output of 5 kW and was named 'Bacon Cell' after the name of its inventor [1], [2]. At the October of 1959 Harry Karl Ihrig, an engineer of 'Allis-Chalmers Manufacturing Company', presented a tractor of 20 Hp which was the first vehicle ever that used a fuel cell [1]. During the 60's, 'International Fuel Cells' company that resides in Windsor, Connecticut developed a 1.5 kW fuel cell for the production of electric power for Apollo spacecraft. This fuel cell was producing both electric power and potable water for the astronauts. This fuel cell was very reliable due to the fact that even after of 10000 hours of flight and 18 missions didn't present any problem at all [3], [4]. The same company developed an even powerful fuel cell during the 70's for covering the needs of NASA space shuttle Orbiter. The reliability of the fuel cells used in this space shuttle should have been extremely high due to the absence of backup batteries. Every fuel cell had a power output of 12 kW in continuous use and 16kW for short periods of time. The fuel cells used in Orbiter showed a very important technological development since they were producing 10 times more power in the same size. Fuel cells had shown great reliability degree of 99% and until today they have been used in 106 missions and in more than 82.000 hours of operation [4], [5].

1.2 State of the art

Fuel Cells are essentially static devices that directly convert the chemical energy of a fuel into electrical energy. The fundamental structure of a fuel cell, as it can be seen in Fig. 1 consists of three main components: the electrodes (an anode and a cathode) separated by a solid membrane acting as an electrolyte. The fuel mix used for feeding a fuel cell is either H_2/O_2 or H_2/air. The hydrogen follows a series of channels to the anode where it dissociates into protons that, in turn, flow through the polymer electrolyte membrane to the cathode and the electrons are collected by an external circuit which is linking the two electrodes as electrical current [6]. The oxidant used is either O_2 or air which also follows a similar series of channels to the cathode where by combining the oxygen molecules with the electrons in the external circuit and the protons coming through the membrane it produces water. When the fuel cell is fed with hydrogen at its anode and oxygen or air at its cathode then the following chemical reactions occur:

Anode reaction: $H_2 \leftrightarrow 2H^+ + 2e^-$

Cathode reaction: $2H^+ + 2e^- + ½O_2 \leftrightarrow H_2O$

Overall reaction: $H_2 + ½ O_2 \leftrightarrow H_2O$
The products of this process are DC electricity, liquid water and heat.

Fuel Cells are expected to play a very significant role in the future energy scenario where the hydrogen economy is believed to take place with the hydrogen being the energy carrier of the future [7]. One of the most promising types of fuel cells that could be used for portable [8], [9], [10], [11], [12], [13], mobile and residential applications is that of Polymer Electrolyte Membrane or Proton Exchange Membrane (PEM) due to their several advantageous characteristics. PEMFC are characterized by high efficiency, low emissions, low operating temperature, low noise levels and high energy density along with the ability to operate without needing an auxiliary fan or compressor to compress the air supply [14].

Along the past 20 years significant research has been done on PEMFC both in experimental and simulation level. Work on PEMFC's is at present in progress in many laboratories in Canada, USA, Japan and several other countries around the world [15]. A sector which receives much interest is that of the air-breathing sub-kilowatt PEMFC due to the fact that the FC's of this type are ideal for mobile applications on decentralized locations. However, there are only few published data regarding information on this type of PEMFC and more specifically concerning commercially available types of PEMFC which is the subject of this study.

At present the experimental research is focused on the effect of the individual components of the PEMFC on the overall performance of the cell along with the investigation on the influence of specific environmental parameters on the performance of the PEMFC. More specifically some of the aspects that draw most of the attention on the research for improving the performance of the PEMFC are the effect of the physicochemical characteristics of the membrane material which was extensively analyzed by Wakizoe et al. [16] and simulated by Cheng et al. [17], the processes, losses, and electrical characteristics of a Membrane-Electrode Assembly (MEA) of a PEMFC which were evaluated by Lee and Lalk [18], the water and thermal balances that were described by Picot et al. [19] and finally the cathode catalyst layer which was analyzed by You and Liu [20] using a parametric study. Also, the behaviour and the performance of a PEMFC were discussed under fast load commutations by Hamelin et al. [21].

Chu and Jiang [22] have evaluated the performance of an air-breathing PEMFC stack under different environmental conditions such as relative humidity and ambient temperature. The performance of the PEMFC stack was analyzed by using an empirical equation and the obtained results were excellently fitted to the experimental polarization curves at various humidity and temperatures.

Wang et al. [23] investigated the parameters affecting the performance of an air-breathing

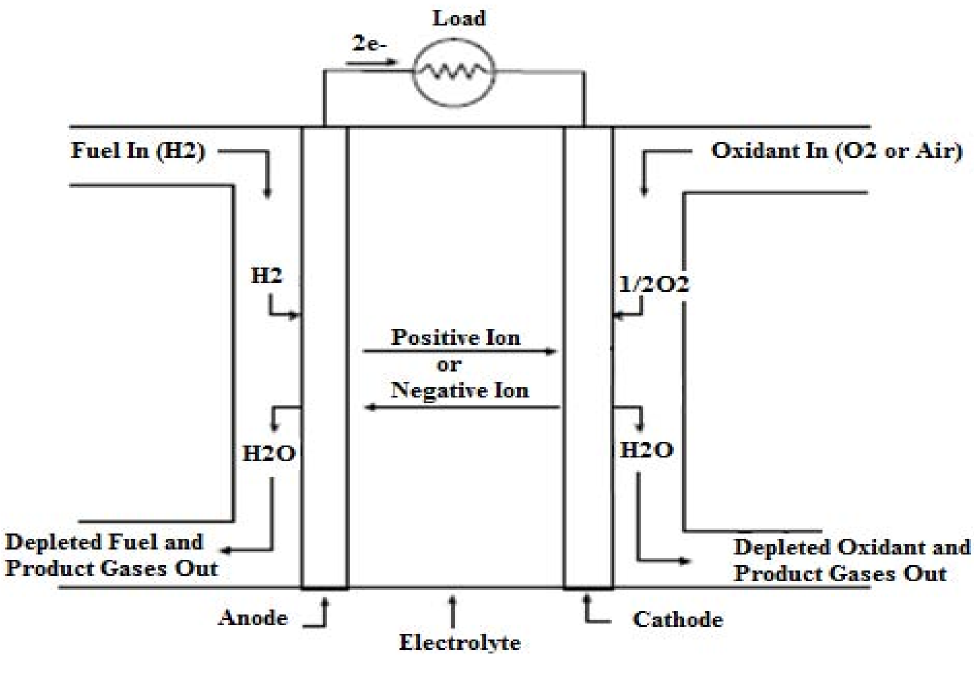

Fig. 1 Operation of a PEM fuel cell

PEMFC through both an experimental and a simulation process which were conducted simultaneously and showed that the performance of the PEMFC is strongly affected by the natural convection feature. Also, from the results coming out of this study it was concluded that the ambient relative humidity along with the distribution of water and reactant and the temperature were greatly affecting the overall performance of the cell.

In another study Ferng et al. [24] analytically and experimentally investigated one single PEMFC. More specifically they have studied the performance of the PEMFC along with the effect of several parameters such as operating temperature and pressure and also the flow characteristics within the cell. The conclusions coming out of both the experimental and the simulation process showed the positive effect that is caused on the cell performance due to temperature and pressure. Also, a validation of the model used was conducted through the plotting of the performance curves of the cell.

In their study Jung et al. [25] have experimentally evaluated an ambient forced-feed air-supply PEMFC in a way to help promote better understanding of the stack design of such fuel cells. Additionally, they have investigated the steady-state performance and transient response for H_2/air PEM fuel cells under a variety of load cycles and operating conditions together with the investigation of the effect of several parameters such as H_2 and air humidity to the performance of the PEMFC.

It should be noted that some of the aforementioned papers and in general most of the papers, which experimentally evaluate PEMFC's, are concerned with high capacity fuel cells while the aim of the present work is to investigate the performance and the stability of a commercial air-breathing 100 W PEMFC stack system through an experimental and a simulation process and to propose interventions for the improvement of the performance of the commercially available PEMFC systems.

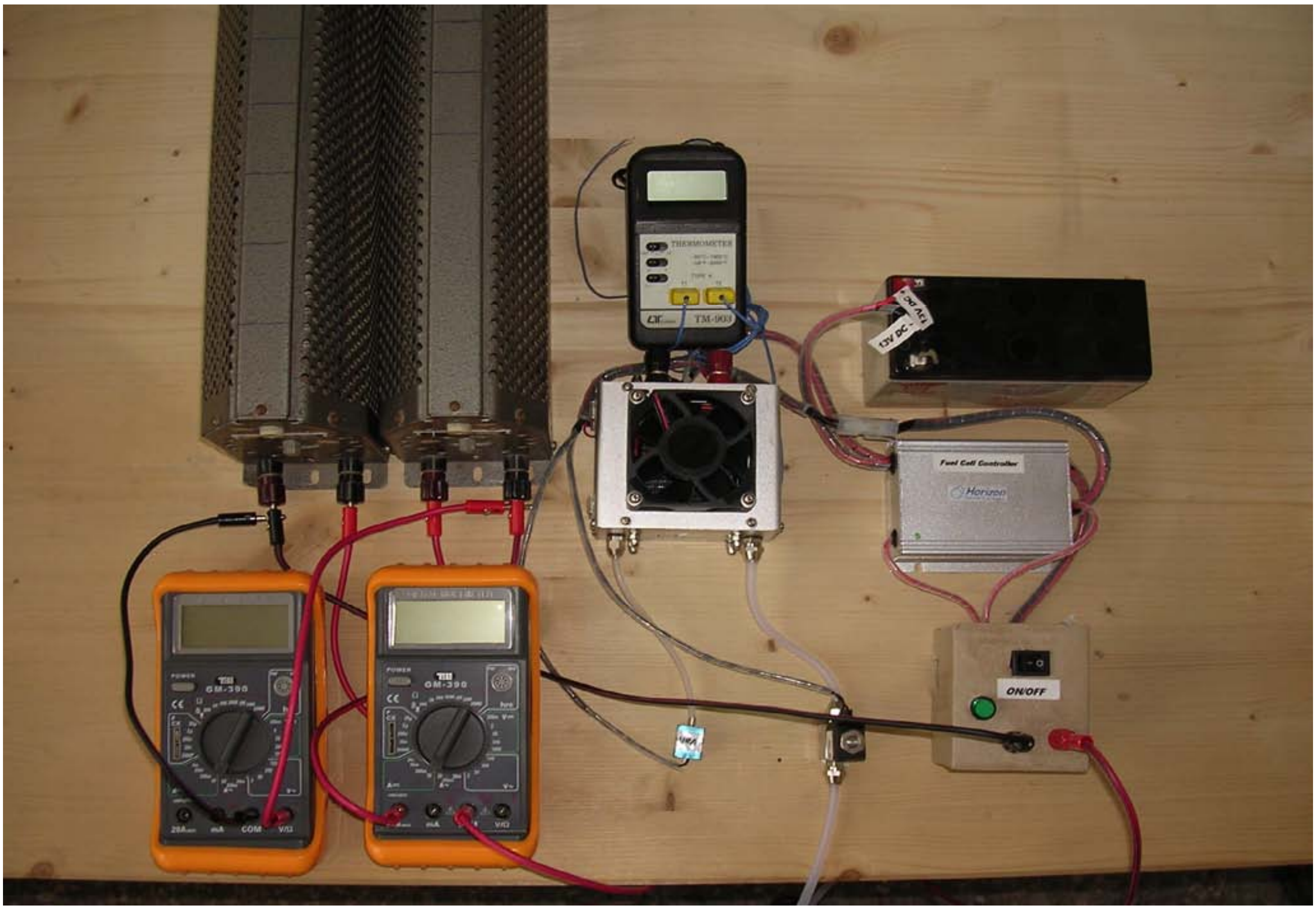

Fig.2 Experimental setup of the 'H-100FC' system

2 Experimental setup

The first part of the work is the experimental investigation of the performance of the Polymer Electrolyte Membrane Fuel Cell (PEMFC) stack.

The PEMFC stack used for the experiment is part of a commercial PEMFC system which is called as 'H-100FC' and is located at the Renewable Energy Laboratory of the TEI of Athens. The 'H-100FC' system consists of a fuel cell stack, two electronic valves, an integrated cooling fan and the control electronics as it can be seen in Fig.2. The PEMFC stack is consisted of 21 cells which are constituted from a negatively charged electrode (cathode), a positively charged electrode (anode), and a polymer electrolyte membrane. Also, for the hydrogen supply of the PEMFC system a steel hydrogen storage tank of 200lt capacity equipped with a proper gas regulating valve is available at the Renewable Energy Laboratory.

During the experimental procedure the PEMFC system is connected with an electrical load, which practically is a series of variable resistances, and by altering the value of the resistances the stack current and voltage are measured using an ammeter together with a voltmeter.

The results of the acquired measurements were analyzed and then used to plot several characteristic curves of the fuel cell stack two of which are the Polarization and the Stack Power-Current.

3 Simulation

PEMFC models are of vital importance for the further development and study of PEMFC. For the last 15 years fuel cell modeling has received much attention due to the fact that the scientific community was trying to acquire deeper understanding of the phenomena occurring within the cells. The general aim of a fuel cell model is to provide a framework for analyzing the performance of a PEMFC system and its components and also to supply the values of some internal variables that are difficult to measure such as the water content inside the flow fields [26]. The models normally focus on one aspect or region of the fuel cell only.

The three main categories in which the fuel cell models can be separated are: analytical, semi-empirical and mechanistic or theoretical. The main difference between these three categories has to do with the way they use to develop a fuel cell model.

The model used for the simulation of the PEMFC in this work is the TYPE 170 of the TRNSYS models library and is a generic mathematical model of a PEMFC. The model is largely mechanistic, with most terms being derived from theory or including coefficients that have a theoretical basis. The major non-mechanistic term is the ohmic overvoltage that is primarily empirically based. The main equations of the electrochemical model are described in published literature [27]. A thermal dynamic model is also included. The theory behind the thermal model is found in previous PEMFC-modelling work [28], while the recommended thermal coefficients were derived from two sources [29], [30], [31].

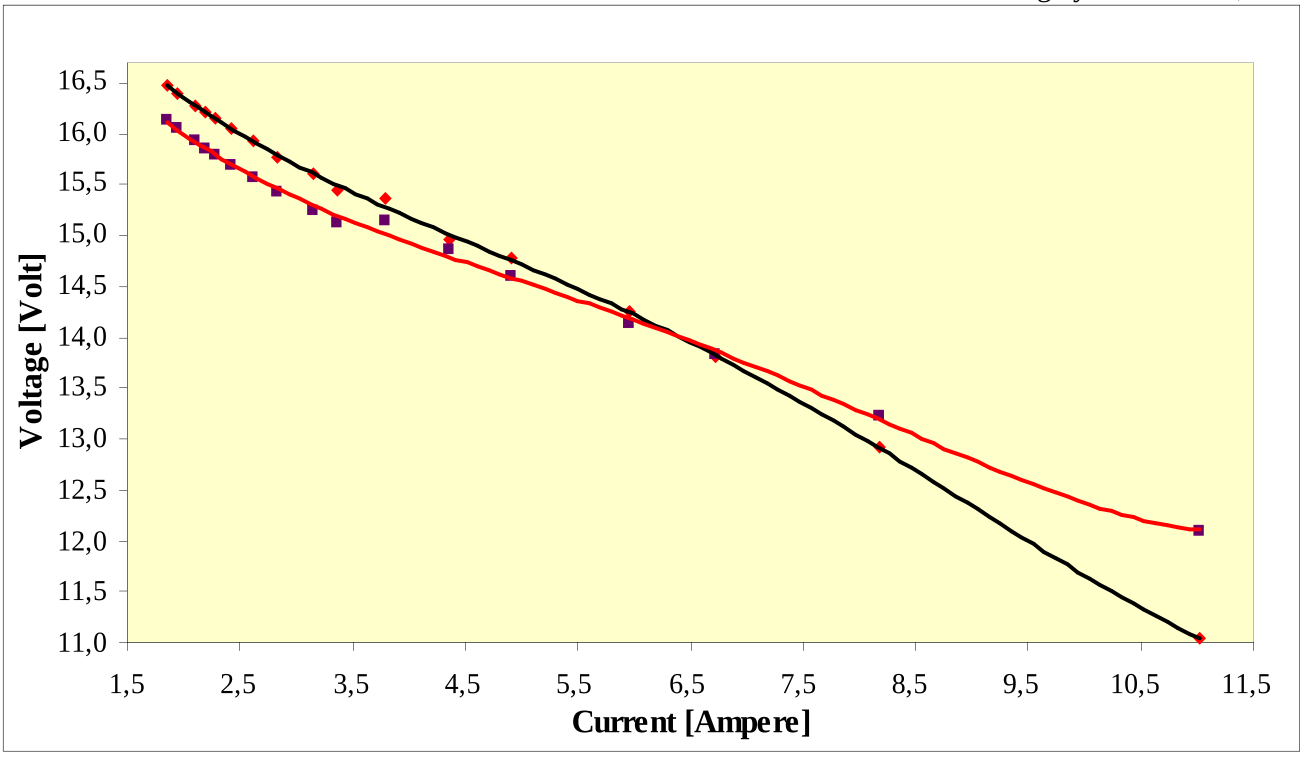

Fig.3 Experimental and theoretical Polarization curves

Since the model is properly modified and the specific inputs and parameters of the fuel cell system are inserted into TRNSYS then the simulation was run and the results were analyzed and represented graphically.

4 Results and Discussion

The experimentally acquired data concerns the voltage, the current and the stack temperature. Also during the entire experimental process the ambient temperature was measured and found to be constant at 25°C. The stack power was calculated by multiplying the stack voltage with the stack current.

As it can be observed in Fig. 3 and Fig. 4 both the experimental and the simulation curves are limited

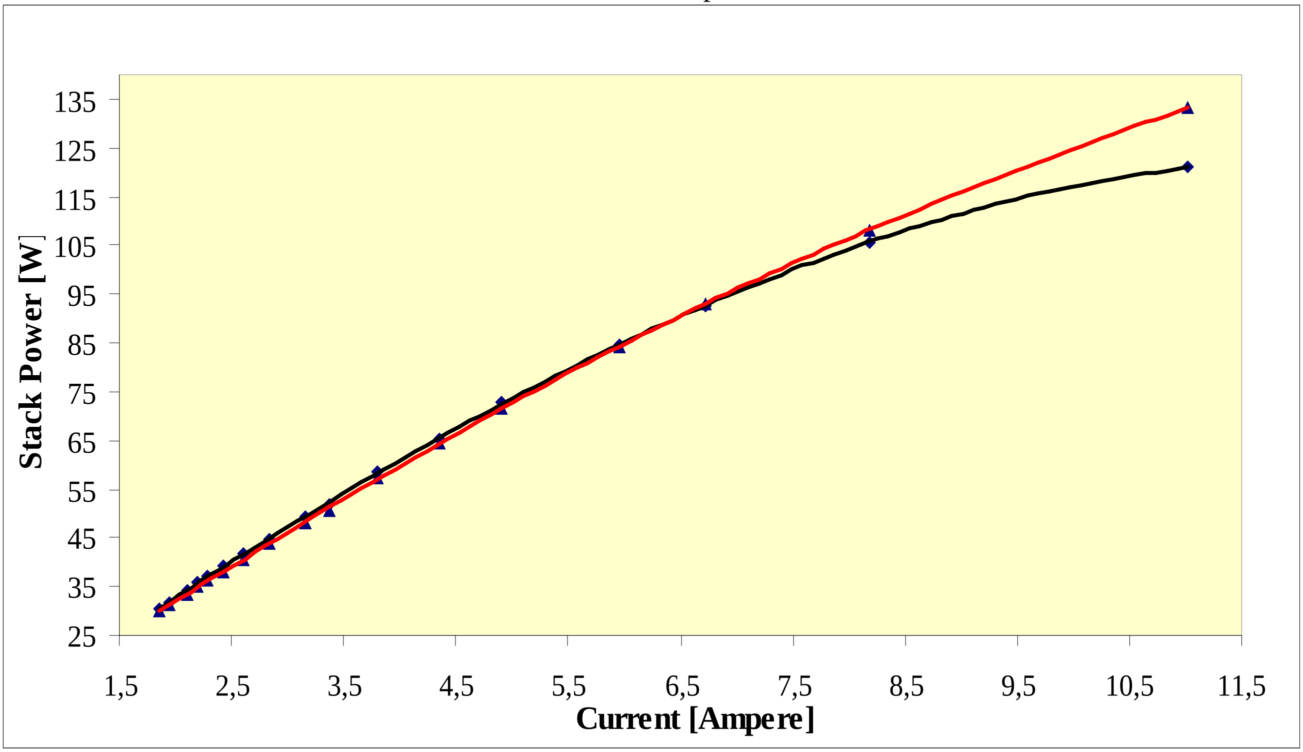

Fig.4 Experimental and theoretical Stack Power curve

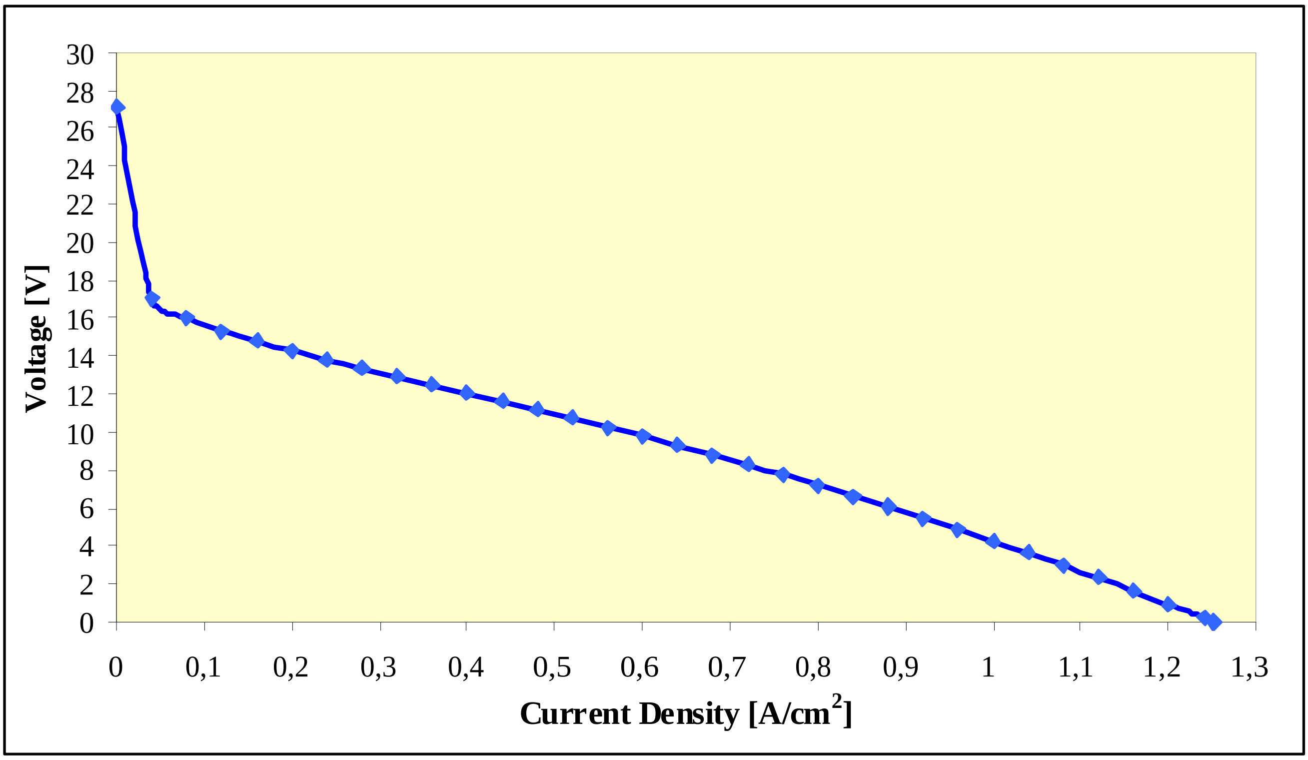

Fig.5 Polarization curve in the whole range of values

to a certain range of current, voltage and stack power values due to the fact that the electronic control unit is limiting the range in which the fuel cell stack works in order to preserve and protect the device from entering a dangerous range in which it might be seriously damaged or even completely destroyed.

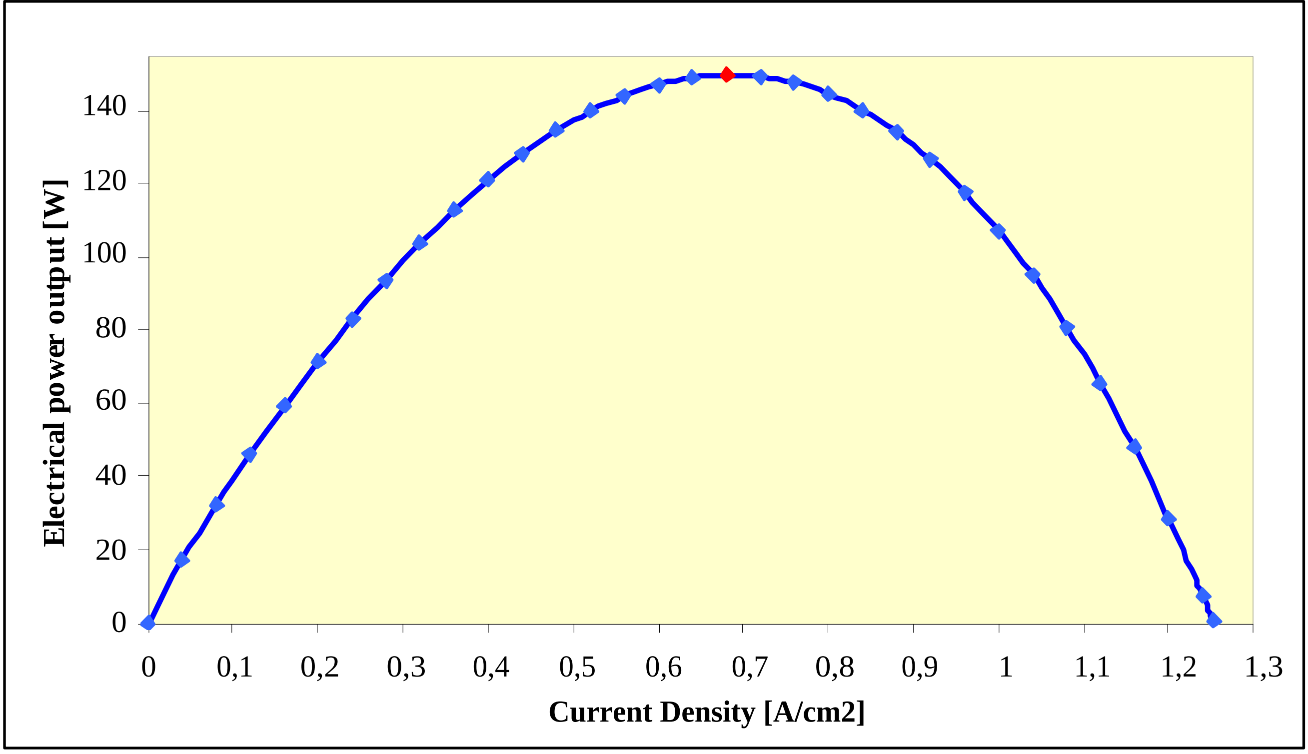

Fig.6 Stack Power curve in the whole range of values

As it can be seen in Fig. 3 the relation between the output voltage and the output current, in the examined range for both Polarization curves, is that they are reversely proportional meaning that when the current increases the voltage decreases in an almost constant slope. The maximum voltage reached in the Polarization curve is 16.49V at 1.85A (experimental), 16.13V at 1.85A (simulation) and the maximum value of the current is 11.02 A at 11.04 V (experimental) and 11.02 A at 12.10 V (simulation).

In Fig. 4 the relation between the stack power and the current can also be observed which is obviously proportional due to the fact that, in the examined range of values, when the current increases then the stack power also increases. The maximum stack power reached during the experiment is that of 120.91 W at 11.02 A and during the simulation process is 133.31 W at 11.02 A.

The comparative study was carried out between the model results and the experimental data in order to help validate the model, primarily for the purpose of establishing confidence in the model when used with sub-kilowatt PEMFC stacks. As it can be observed in Fig. 3 and Fig. 4 both the simulated Polarization and Stack Power curves show good agreement with the experimental ones while the difference between them is in the range of (-2.16)-9.63% (Polarization) and (-1.64)-10.26% (Stack Power) which are certainly low difference ranges.

The difference between the model results and the experimental is caused by a variety of error sources like those described below:

-The model does not accept lower active membrane surface than $25cm^2$ while the active membrane surface of this PEMFC stack is $18cm^2$.

-The human factor concerning the reading of the analogue manometer used to measure the pressure of the hydrogen.

-The integrated air fan that by its interrupted operation, which is controlled by the control electronics, does not allow the stack to preserve a constant temperature over its operation period and instead of that the temperature is continuously increasing and decreasing.

Due to the fact that when using the simulation process the limitations occurring from the operation of the control electronics do not affect the process we were able to plot both the polarization and the stack power curve for the whole range of values in Fig. 5 and Fig. 6. In these figures both curves are plotted as a function of current density instead of current in order to give a more representative picture of the capabilities of the specific PEMFC system. The value of the open circuit voltage is 27.09 V

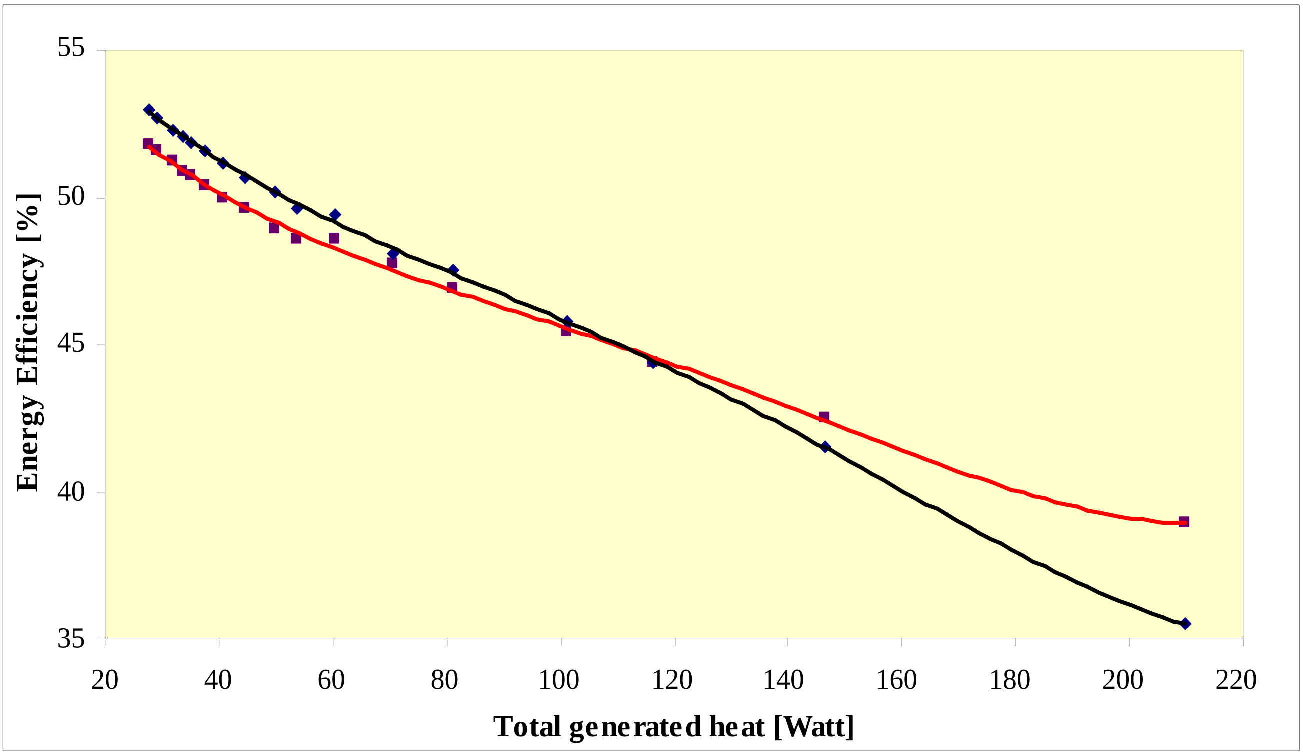

Fig.7 Energy Efficiency as a function of Total generated heat

while the value of the short circuit current is 31.3 A. Also, the maximum theoretical value of the stack power is 149.78 W for a current value of 17 A or a current density value of 0.68 A/cm^2 and a voltage value of 8.8 V.

Fig. 7 shows the energy efficiency if the stack as a function of the total heat generated which are essentially the thermal losses in the form of heat exchanged with the surrounding environment. Due to the fact that the thermal losses are directly related to the current and the energy efficiency is directly related to the stack voltage as it can be observed the shape and the slope of this curve is the same as the Polarization curve. Nevertheless, Fig. 6 is also important due to the fact it gives a clear picture of the total heat generated by the PEMFC stack.

In Fig. 8 the hydrogen consumption of the PEMFC stack is plotted as a function of stack power. This curve is very useful and easy to understand and use from anyone who wants to buy such a system due to the fact that it essentially shows the hydrogen consumption for each specific stack power output. The hydrogen consumption was calculated using the simulation model.

5 Conclusions

In this study the performance and the stability of a PEMFC stack system were investigated through an experimental and a simulation process. The results of the current study indicate some very useful conclusions concerning the operation and the further development of sub-kilowatt PEMFC systems.

For most applications and especially steady state operation a PEMFC does not have to operate at the maximum possible power due to the fact that there the energy efficiency of the system is the lowest. So, when a PEMFC of a specific power is needed then the choice should be oriented towards higher nominal cell potential due to the fact that the PEMFC will operate with better energy efficiency, due to the fact that it will operate at the optimum point of operation, and the savings from this fact will offset the cost of the additional cells.

As the validation of the model is concerned it can be observed that the simulation curves are in good agreement with the experimental data inspite of the existance of several error sources. These results increase the confidence of this specific model when used for air breathing sub-kilowatt PEMFCs.

The hydrogen consumption of this PEMFC for specific output power values is rather acceptable and

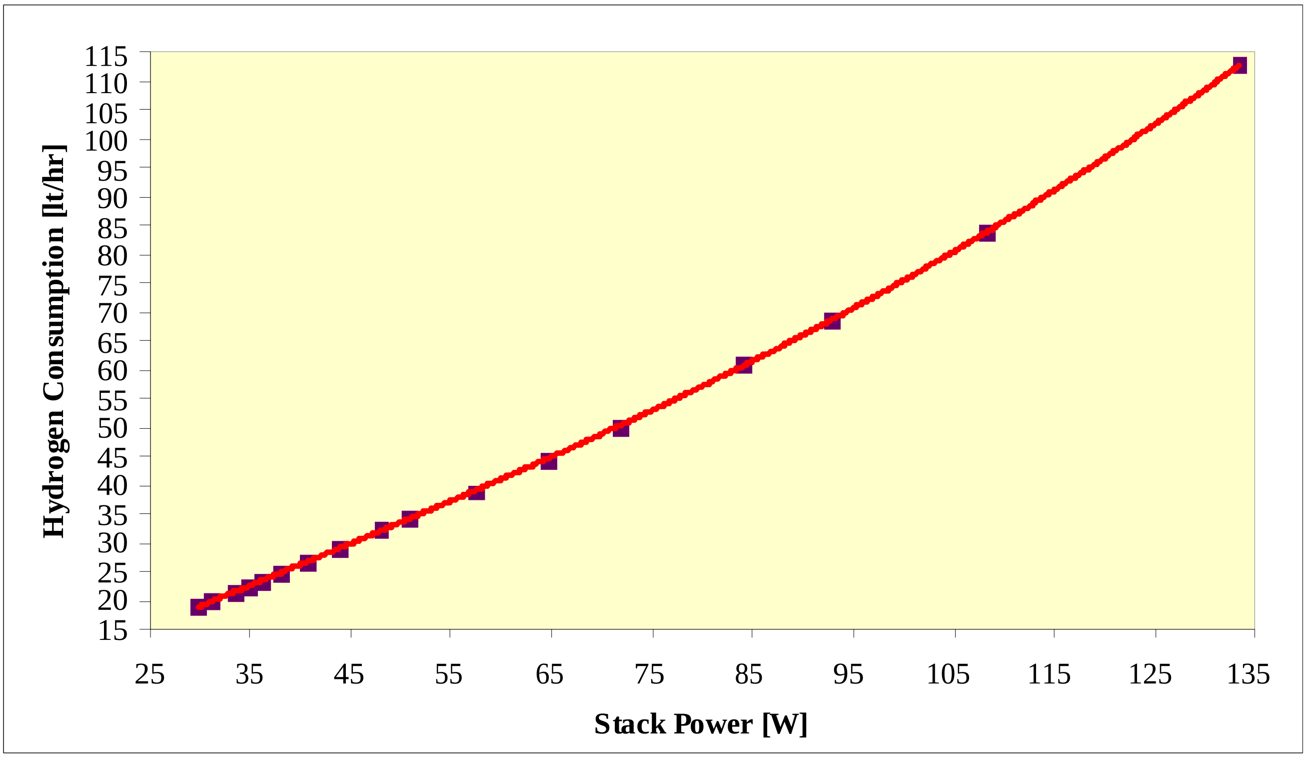

Fig.8 Hydrogen consumption as a function of Stack Power Output

affordable in terms of economic viability since it can deliver 100 W of electrical power by consuming just ~72lt/h hydrogen. From this fact it can be concluded that this specific PEMFC stack system can be used for mobile or desantralized applications as a power source since it does not need a very large hydrogen storage tank but this is directly dependent on the specific application and its needs.

The maximum total generated heat for the studied stack is negligible (~210 W) while it also has a low temperature (~60°C) to have any practical use for even a small heating application.

All of the proposed interventions for the improvement of the performance should be evaluated in terms of economic viability and balanced against the energy and the cost required for them to be applied. For example the additional energy required to pressurize the reactant gases in comparison with the consequent increase in the performance.

A series of interventions for the improvement of the performance of this commercial PEMFC stack is proposed.

A study could be conducted to investigate the possibility of developing a more sophisticated and complex cooling system in order to maintain the temperature of the stack in high levels, but always below the maximum, so that the stack will almost always operate in the nominal conditions. Additionally, if the temperature of the stack is achieved to be constant in rather high levels then the amount of the generated heat will also be increased and the possibility that is affordable and useful to be used must be examined.

In the specific PEMFC system the use and the integration of an oxygen-air pump could be evaluated both in terms of economic viability and also in terms of increasing the PEMFC performance and energy efficiency since as it was concluded above the cathode pressure highly affects the performance of the PEMFC system.

Finally, another aspect that could also be investigated in spite of its simplicity it's the matter of packaging of the PEMFC system into a case in which it could also include a small hydrogen tank and it could be transported rather easy and provide electrical energy for a certain period of time and power to isolated decentralized areas.

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