DESIGN AND PERFORMANCE ANALYSIS OF PROTON EXCHANGE MEMBRANE FUEL CELL

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Abstract:

The analysis has been focused in the start up and shutdown processes because they allow analysing the influence of different parameters. In this sense, the evolution of the stack and the environment temperatures can be observed, which allows measuring the heat released by the fuel cell. On the other hand, the partial pressure equation of the hydrogen is included in the PEMFC mathematical modeling to study the PEMFC voltage behaviour related to the input variable input hydrogen pressure. The efficiency of the model is 33.8% which calculated by applying the energy conversion device equations on the thermal efficiency. PEMFC's voltage output performance is increased by increasing the hydrogen input pressure and temperature. The polarization curves of the fuel cell were plotted under similar operating conditions with different MPL. These results provided a wide and cheap choice of hydrophobic agents in the MEA

1.0 Introduction

The reduction in fossil fuel resources and the environmental impacts that are associated with the use of these fuels influence the sustainability of future energy systems. Therefore, alternative energy sources and their more efficient utilization has been a major concern for researchers in recent years. Many consider fuel cells to be promising in this regard, as they use clean energy and have reduced greenhouse gas emission. In addition, the Carnot cycle efficiency does not limit their efficiency and they do not emit pollutants, such as sulfur dioxide and nitrous oxides. Proton exchange membrane fuel cells (PEMFCs), among other types, are expected to play a major role in the future energy sector due to their high power density, quick starting, low operating temperatures, and simple stack design.

However, reducing the capital costs, weight, and volume of these fuel cells is a challenge in making them competitive with traditional power producing systems like internal combustion engines. In addition, it is necessary to have an appropriate and optimum value of water content inside PEMFCs to retain the durability of these fuel cells and the efficient operation of them. This can be achieved by humidifying the reactant gases before they enter the cell [3,4]. Semi-empirical and numerical models have been introduced in the literature in order to predict the variation of voltage with current density of a PEMFC and to understand and improve the performance of PEMFC systems. These models are also capable of predicting the fuel cell performance for engineering systems applications.

This section briefly reviews a selection of previously reported works that are related to the semi-empirical models. when considering such operating parameters as the partial pressures at the electrodes, the operating temperature, and the fuel cell current. Some other researchers have used semi-empirical models for simulating PEM fuel cell performance. The waste heat from these fuel cells is in the range of 50 ◦C to 100 ◦C, so that its recovery for performance enhancement is considered to be a technical challenge. A few papers in the literature have dealt with the utilization of PEMFC waste heat.

2.0 Literature Review

Fallah, M.; Mahmoudi, S.M.S.; Yari, M (2018) Bipolar plates are the important components of the PEM fuel cell. The flow distribution inside the bipolar plate should be uniform. Non-uniform flow distribution inside the bipolar leads to poor performance of the fuel cell and wastage of expensive catalyst. A single channel PEM fuel cell is taken and electrochemical analysis is carried out on it. The results are compared with the available published experimental data obtained by other research group, and they are found to be in good agreement. A baseline design of the bipolar plate is taken and numerical analysis is carried out. The results show that the flow distribution is non-uniform. The baseline design is changed to an improved design to obtain a uniform flow. The improved design yielded a uniform flow. A single channel is taken from the improved design of the bipolar plate and electrochemical analysis is carried out on it. The geometry of the fuel cell channel is changed from rectangular to square, semi-circle and triangular shapes and the performances of the fuel cell are observed. The performance of the rectangular channel is found out to be the best, and the performance of the triangular channel is poor compared to rectangular channel design.

Mert, S.O.; Dincer, I.; Ozcelik, Z (2007) Comprehensive exergy and exergoeconomic assessments are reported for a proposed power producing system, in which an organic Rankine cycle is employed to utilize the waste heat from the fuel cell stack. A complete mathematical model is presented for simulating the system performance while considering water management in the fuel cell. The simulation is performed for individual components of the fuel cell system, e.g., the compressor and humidifiers

Chen, D.; Peng, H. A (2005)A theoretical model of a combined system composed of a high-temperature proton exchange membrane fuel cell (HT-PEMFC), a regenerator and an absorption refrigerator (APR) is established, where the APR is used to absorber the waste heat from HT-PEMFC for cooling production.

Afshari, E.; Houreh, N.B (2014) To satisfy high power density demand in proton exchange membrane fuel cells (PEMFCs), a robust control strategy is essential. A linear ratio control strategy is examined in this work. The manipulated variables are selected using steady-state relative gain array (RGA) analysis to be the inlet molar flow rates of hydrogen and coolant, and the controlled variables are average power density and average solid temperature, respectively. **Chang, H.;**

Wan, Z.; Zheng, Y.; Chen, X.; Shu, S.; Tu, Z.; Chan, S.H. (2017)A single channel PEMFC is taken and validated by comparing the numerical results with the published experimental data in the literature. The obtained results are in good agreement with the available published experimental data. The validated parameters are then applied to the future designs. An improved design of the bipolar plate is developed for uniform flow. The flow channel geometry is changed to different shapes and the performance is observed.

Chahartaghi, M.; Kharkeshi, BA. (2018) In order to reuse the waste heat of HT-PEMFC, an APR is integrated with the fuel cell for cooling production. By considering the existing thermodynamic-electrochemical irreversible losses within the combined system, the equivalent power output and efficiency of the HT-PEMFC, the APR and the proposed system are calculated.

Romdhane, J.; Gualous, HL (2018) We have studied the transient and input–output responses obtained from a distributed parameter model of the PEMFC, and found that the PEMFC does not exhibit a sign change in the gain of the plant with the inlet molar flow rates of hydrogen and coolant as the manipulated variables. Hence, linear controllers with fixed gain are implemented to satisfy higher power density demand. A ratio control strategy is able to overcome the problem of oxygen starvation; however, the performance of the linear controllers is slow due to the presence of nonlinearities in the dynamic response of the PEMFC.

Ebrahimi, M.; Derakshan, E. (2018) The output performance of the PEMFC electric vehicles was compared under different operating parameters by keeping the other parameters constant. Simulation results show that the driving temperature affected the PEM fuel cell power achieved greatly under the same auxiliary load. The aggressive cycle may need more flow rate and achieved more fuel cell power by compare with the fuel economy driving cycle test under the same auxiliary load and the same hydrogen storage system.

Arsalis, A (2019) In this paper, a direct power generation method that places a hybrid system (comprised of a 12 kW PEMFC and battery) at the rack level, only inches from the servers, is tested and characterized. By using this design, the power distribution system in the data center and the grid outside of the data center can potentially be eliminated. The steady state performance and the transient response of the PEMFC system and the battery in response to AC loads and real server loads have been evaluated and characterized.

Wang, C.; Nehrir, M.H.; Shaw, S.R. (2005) The configuration of the flow channel on a bipolar plate of a proton exchange membrane fuel cell(PEMFC) for efficient reactant supply has great influence on the performance of the fuel cell. Recent demand for higher energy density fuel cells requires an increase in current density at mid voltage range and a decrease in concentration overvoltage at high current density. Therefore, an interdigitated flow channel where mass transfer rate by convection through a gas diffusion layer is greater than the mass transfer by a diffusion mechanism through a gas diffusion layer was recently proposed.

3.0 Methodology:

Data were analyzed it was extracted from the SCI-Expanded online version of Thomson Reuters Web of Science, where the filter by title was used for the search keywords proton exchange membrane fuel cells. SCI-Expanded is highly and frequently used to broad scientific achievements in all areas of science. The software used to process the WoS files (Web of Science) was HistCite TM, it generates historical maps of bibliographic collections resulting from searches of subjects, authors, institutional journals or sources in the ISI Web of Science. The

software generates chronological historiographies that highlight the most cited works in the recovered collection; other listings include classifications by authors, journals, institutions, countries, cited documents and keywords. The analysis and classification of scientific results, subject categories, journals, authors, countries, and institutes were elaborated manually and processed in Microsoft Excel 2016 and OriginPro 8.

CiteSpace software was used in combination with Ucinet 6 to generate international collaboration networks. The ArcGIS software was used to process

distribution of publications using cartographic representations.

Numerical modelling involves three major steps. The first step is the creation of fuel cell geometry. Solidworks 2017 is used for this purpose. The second step is the creation of mesh, ICEM meshing module available in ANSYS Fluent 15.0 is used. The last step is the analysis part. A block diagram depicting this sequence is shown in figure.

Figure Flow diagram of modelling

The assumptions made in the numerical modelling are: steady state, single phase, laminar flow, gases are compressible ideal gasses, the by-product water is in liquid phase and heat transfer inside the cell is only through conduction. The physical phenomena occurring in a fuel cell can be represented by solutions of conservation equations like mass, momentum, energy, species and current transport. In addition, equations that deal specifically with a phenomenon in a fuel cell may be used Stefan- -Volmer equation, Ohms law and so on.

To obtain a micro PEMFC polarization curve, the micro PEMFC test has a gas supply unit, electrical load, power supply, computer, fuel humidifier, fuel temperature controller and mass flow controller. Fig shows the experimental setup. The gas supply unit provides fuel and the oxidant to the micro fuel cell. The electrical load is a device that simulates loading on an electrical circuit. Counter to the current source, the electrical load is a current sink. The load current is regulated electronically. The range of measured currents is 015 A and maximum power output is 75 W. The power supply supplies electricity to each component in this experimental test. A computer regulates all installations orders and evaluates experimental results. The micro PEMFC structure cannot be heated because the end plate is made of acrylic resin. Therefore, a humidifier and temperature controller are used to humidify and heat the fuel to improve micro PEMFC performance.

The flow rates of hydrogen, oxygen and air are regulated by mass flow controllers. Notably, the flow rate through this mass flow controller cannot be ˘10 cm3 ·min¯1 in the anode and 20 cm3 ·min¯1 in the cathode. The micro PEMFC is connected to the electrical load. Polarization curves are plotted after the micro PEMFC reaches a steady state. Various fuel temperatures and fuel flow rates are tested. The fuel flow rates that generate a current of 1 A are calculated based on the theoretical volume. The flow rates of hydrogen and oxygen are 7.6 and 3.8 cm3 ·min¯1 ·A¯1 , respectively. Therefore, the flow rates are multiplied by the stoichiometric value of 1.37 to obtain a value of 10.4 cm3 ·min¯1 ·A¯1 for the anode, and 1.84 to yield 7.0 cm3 ·min¯1 ·A¯1 for the cathode.

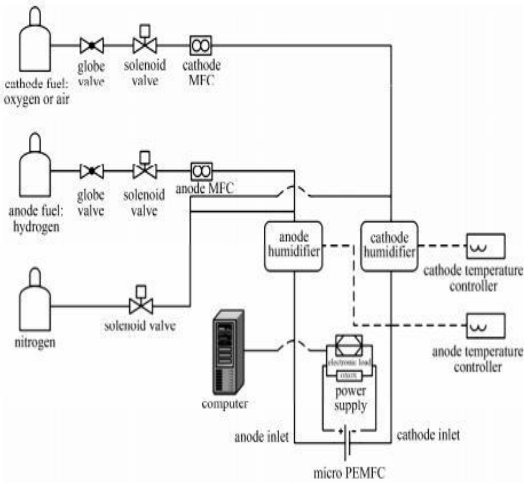

Figure Schematic diagram of the experimental setup

Thermodynamic analysis was performed by utilizing the Matlab Simulink modeling platform. Dynamic (time-variant) modules coupled with the thermodynamic properties database and equilibrium composition solvers from Chemkin (commercial software originally developed by Sandia) were modified where needed and combined to model the complete aircraft PEM fuel cell systems

To reject the waste heat from the fuel cell power production, an internal water-based cooling circuit took the heat from the stack to a heat exchanger, where the heat was transferred to an external cooling circuit and rejected by a cooling subsystem external to the fuel cell rack using an external chiller.

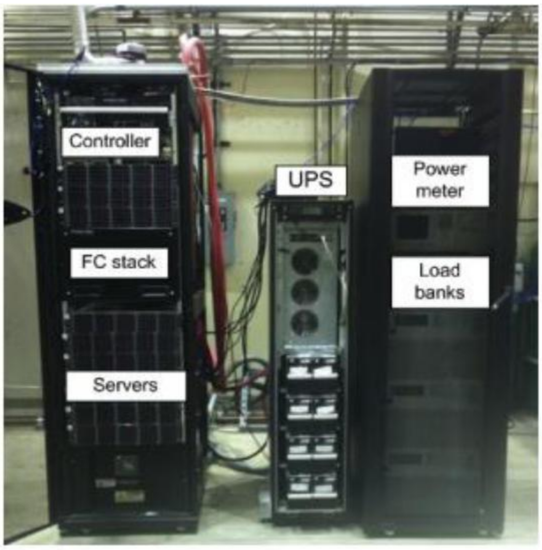

Figure The hybrid system tested.

Anode and cathode exhausts from the fuel cell stack were removed via a blower in the ventilation system which provides continuous ventilation and under pressure inside the fuel cell system. In the hybrid system, the power output of the 12 kW in-rack PEMFC system was first converted to 192VDC and then connected to a 10 kV A, 208VAC L-L UPS system to supply AC power to the servers/load.

4.0 RESULTS:

To validate the developed model in MATLAB /SIMULINK environment, the experimental results obtained from the test setup based on the Ballard 5kW PEM fuel cell is used. The stack used in that study consists of 35-cells with a cross sectional area of 232 cm2 for each cell. The membrane electrode assembly used in the model consists of Nafion 117 membrane. Humidified hydrogen and air are supplied at the anode and cathode respectively in which the hydrogen gas is recirculated at the anode. The performances of the Ballard stack model such as cell voltage and stack power versus current density characteristics are shown in Figs.

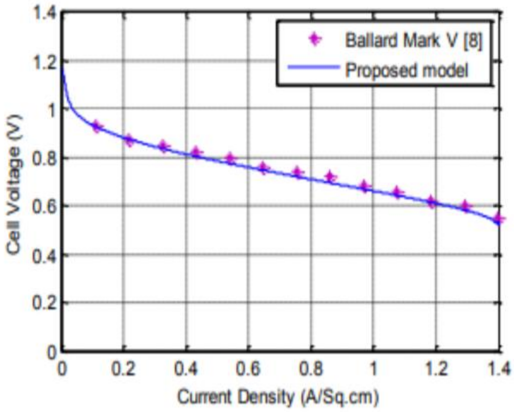

Figure Model validation of the Ballard-Mark-V Polarization characteristics with the developed model for a single cell

Steady state behavior

The steady state characteristic in the form of polarization curve obtained by simulating the model for the standard operating conditions is validated with the experimental results and is shown in Fig. The steady state behavior of a single cell for the proposed model is obtained by simulating it with the standard operating temperature of 72 degree Celsius. The polarization curve is obtained by increasing the load current from 0A (no load current) to 325A over a period of 93 seconds. The predicted polarization curve of the semi-empirical model developed for the PEMFC has good agreement with the published experimental data as shown in Fig. The model developed can perfectly predict the performance of the cell over a reasonably large range of voltages corresponding to current densities of as high as 1.4 A/cm2 . The sudden drop in voltage at the start is due to activation loss and at the end of the curve is due to concentration loss. The linear drop in voltage in the middle between the activation and concentration losses is due to ohmic voltage losses that occur inside the stack.

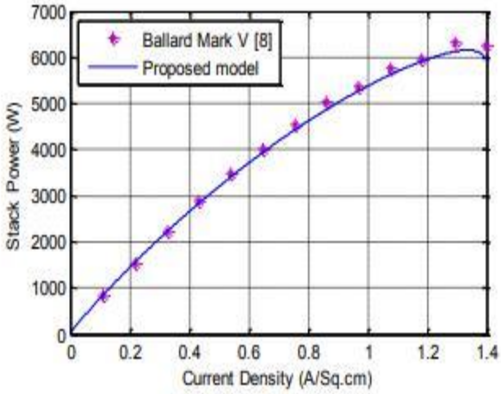

Figure Stack Power – Current Density characteristics of Ballard-Mark-V PEMFC stack System operated at Tstack=72° C

Power versus current density characteristic of the PEM fuel cell stack obtained for the model developed and Ballard model is shown in Fig. The experimental data of stack power is formulated using the polarization data and current density. In this case also, the predicted power characteristic fits well with the experimental data. It can be seen from the power characteristics that the Fuel cell stack has delivered a maximum of 6.3 kW at about 1.29 A/cm2 . The maximum power occurs very close to the concentration loss region and it starts to decrease when the load current is increased further in the concentration zone. This decrease in power output of the stack is due to the sharp drop in the stack voltage as it enters from ohmic region to concentration region. This necessitates the operation of the fuel cell in the ohmic region.

Effect of Membrane hydration

The effect of water hydration over the membrane has a significant impact on the cell performance and is discussed in this section. Water management system includes humidifier that serves in humidifying the feed gases into the stack assisting the membrane with proper water hydration. In addition to humidification, water management system serves in maintaining the proper hydration in the membrane by efficiently removing the water production rate at the cathode chamber. Firstly, the profile of membrane water content for a membrane with proper hydration and without maintaining the water hydration level is analyzed and is shown in Fig. Secondly, the effect of membrane hydration on the polarization loss is analyzed and depicted in Fig. Thirdly, the effect of various degrees of water flooding over the cell performance is summarized and presented in Fig. Lastly, the profile of power density curves for various degrees of water flooding is discussed and is shown in Fig.

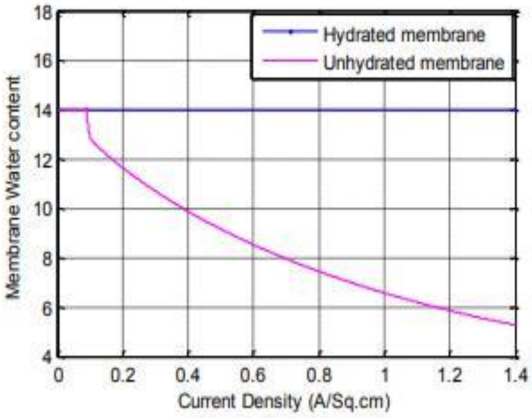

Figure Membrane Water content for a hydrated and unhydrated membrane

Effect on membrane water content

It can be seen that in Fig, the membrane water content is maintained at 14 for different current densities that corresponds to a well hydrated and humidified membrane. A well hydrated membrane is ensured by properly humidifying the fuel and the air before it enters into the stack. Hence the hydrogen fuel and the air are passed through the humidifier before it is fed into the anode/cathode chambers of the PEM fuel cell stack. In addition, the electrolyte membrane used has to be prevented from accumulation of water on it. This happens when the water removal rate is lesser than the water production rate at the cathode which leads to back diffusion of water and results in flooding of membrane. As a result, water removal has to be efficiently done by the water management system and also by well maintained operating temperature of the stack.

The profile shown in Fig. also includes the membrane water content of a membrane used in the fuel cell stack when the reactants are not humidifed. This corresponds to an unhydrated membrane when unhumidified fuel and air are passed on to the anode/cathode chamber of the PEM fuel cell stack and when the water removal rate equals the water production rate at the cathode. Initially at start up, the membrane water content is maintained at

14. Thus the stack performance is analyzed by using a membrane with nominal water content on it at the time of start up and the stack is then gradually loaded in the absence of humidification system with proper water removal rate by the water management system. This leads to a decrease in the level of membrane water content towards 5 from 14 that correspond to a drying membrane when the current density reaches 1.4 A/cm2 . This drying membrane is due to hot pressurized hydrogen fuel and air passed on to the stack without humidification.

Effect on polarization losses

The effect of membrane water content over the cell voltage drop caused by ohmic loss that occurs inside the cell membrane is depicted in Fig.

The effect of concentration loss over the cell voltage drop is neglected in this analysis as the optimal operating point lies only in the ohmic region. Also, the membrane water content has no effect over the activation loss that occurs inside the cell and this can be seen from the cell voltage profile shown in Fig. However, it is seen that the membrane water content has a significant impact over the ohmic loss under hydrated and unhydrated condition. The drop in cell voltage due to ohmic loss for a well hydrated membrane lies within 0.2 voltage while for an unhydrated membrane it drops about 0.6 volt as seen in Fig. Also, the cell voltage comparison shown for a hydrated and unhydrated membrane clearly depicts the requirement of proper water hydration for the membrane to be used in the PEMFC stack so that the net cell voltage will be appreciable.

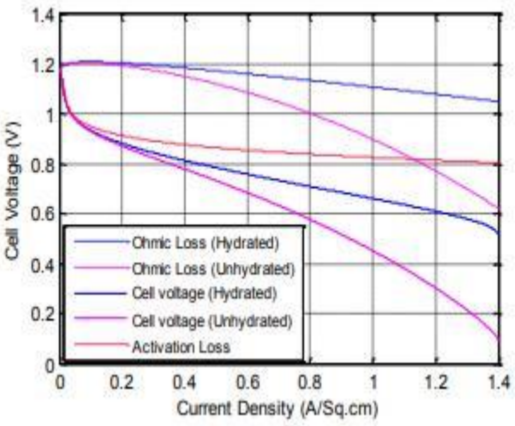

Figure Voltage drop caused by ohmic loss due to hydrated and unhydrated membrane.

Effect of water flooding on polarization curve

In this section, cell voltage performance is analyzed for water flooding at various degrees of membrane water content . Effect of Membrane/water flooding over the polarization curve of a single cell used in Ballard-Mark-V fuel cell stack system is shown in Fig. It illustrates the polarization curves for various degrees of membrane flooding with dissimilar membrane water content such as 14, 11, 7 and 5 that corresponds to the membrane without flooding, light, moderate and heavy flooding respectively. It can be seen in the polarization profile that the slopes of the curves are heavily affected by the flooding of membrane. Accumulation of water occurs at cathode when the water removal rate is lesser than the water production rate which leads to water flooding of membrane. This flooding of membrane is because of back diffusion of water accumulated at cathode towards anode. The flooding of membrane prevents the membrane water content to be at 14.

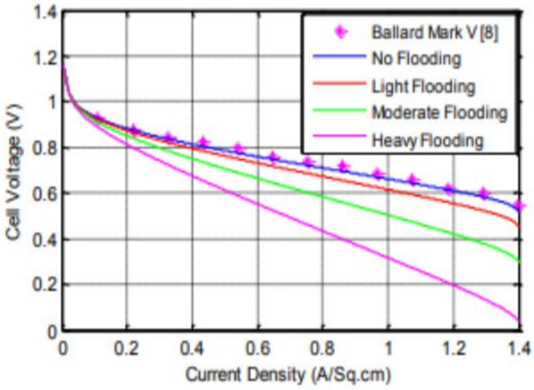

Figure Polarization curves of a single cell for the effect of Membrane/water flooding.

Effect of water flooding on power density

The power density versus current density curves of the PEMFC stack obtained from the experimental results of Ballard-Mark-V and the model proposed is depicted in Fig. 9 for the effects of different water flooding conditions. The model response fits well with the experimental data for the model developed that corresponds to the membrane without flooding condition. Though the operating point for the Ballard-Mark-V fuel cell system is 5kW for a power density of 21.55 W/cm2 , none of the authors has predicted the power performance of the stack beyond its operating point by maintaining MEA water balance. Hence an attempt is made in the proposed work for operating the stack beyond 5kW. It can be seen that the peak power density (27.18 W/cm2) occurs near the fuel cell current density of 1.29 A/cm2 that corresponds to the rated current nearly of 300 A for the Ballard-Mark-V stack system under membrane without flooding condition. Beyond which the power density curve tends to decrease as the stack enters into the concentration zone.

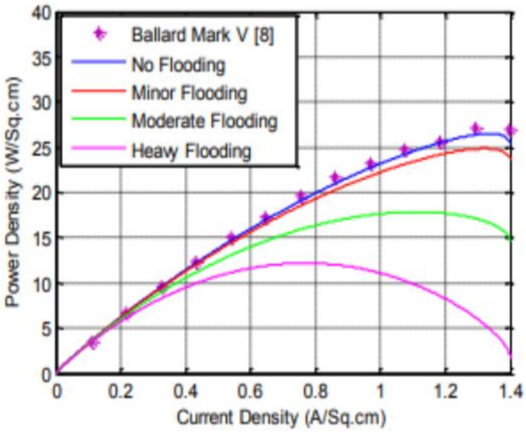

Figure Stack Power Density curves of Ballard-Mark-V for different flooding conditions.

The cathode exchange current density shows a great influence on the polarization curve, being perfectly in-line with the physical explanation already given.

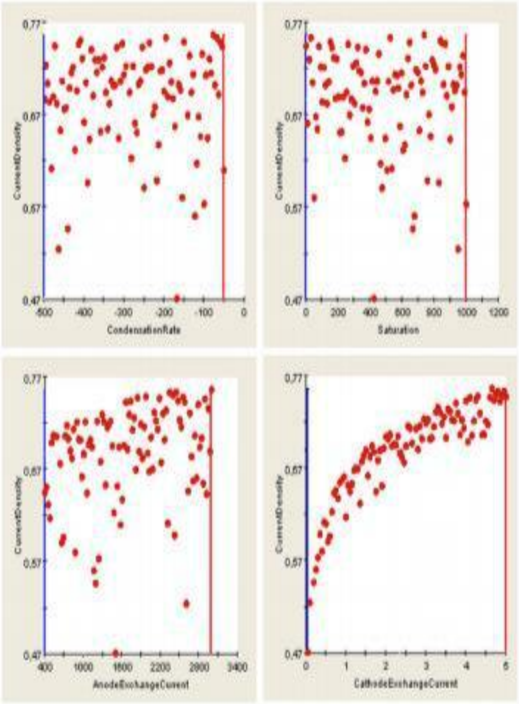

Figure Scatter plots obtained fort the sensitivity analysis of the noise factors. Each red point represents a simulation point of the DoE. For each plot, its corresponding noise factor is given in the x-axis, between its lower and upper limits. The objective function is given on the y-axis.

5.0 Conclusion:

In this sense, different tests have been developed in an electrical micro-grid fed with the fuel cell, where measurements of different parameters have been taken. The higher the temperature and pressure inserted into the system, the better the performance. However, the over supplied input pressure and temperature will damage the membrane of the PEMFC. For further research, the limitation of the input supply and other parameters should consider in the model. These processes play a decisive role in determining the performance of the Fuel cell, so that studies on the phenomena of gas flows and the performance modelling are made deeply. This paper gives a comprehensive overview of the state of the art on the Study of the phenomena of gas flow and performance modelling of PEMFC.

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