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An Investigation into the Characteristics of Proton Exchange Membrane Fuel Cell Based Power System

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Abstract

Fuel Cells (FCs) use hydrogen as their prime fuel source, which promotes them as one of the attractive options for clean energy generators. Although they have been around for some time, their characteristics are not yet fully understood. This paper offers a thorough investigation into the characteristics of proton exchange membrane (PEM) type of fuel cells based power system. The paper firstly presents a concise explanation of the working principles of the PEM electrolyser and FCs supported by novel modelling using MatLab. The simulation results are then validated by a series of experiments carried out on operational 500 mW FC followed by detailed performance parameters of such type of FCs. Parameters affect the efficiencies of each part of the system are investigated and the total system's efficiency is then calculated. The efficiency of the electrolyser and PEM was found to be 85% and 60 % respectively. Polarization curve has been used in order to evaluate FC's performance. From the polarization curve, it is noticed the efficiency of the FC increase with increasing pressure and temperature. The activation losses are reduced when the temperature increased. Moreover, the mass transfer is enhanced towards reducing the PEMFC's resistance.

Keywords: Hydrogen, Renewable Energy, Fuel Cells (FCs), Proton Exchange Membrane FCs (PEMFC), Reliability and Sustainability, Performance Evaluation, Modelling and Simulation.

1-Introduction:

The rising of fossil fuel prices and the growing concerns about the greenhouse gas emissions prompt scientists and researchers to search for other sources of energy that are sustainable with low cost, high efficient energy conversion and minimal environmental impact. Hydrogen and bio-fuels can be used as an alternative clean energy source in the near future. Fuel Cells (FCs) have promising features as they have high efficiency and low emissions (Cultura 2014).There are numerous types of FCs that operate in a similar way, but they differ in operating conditions and the type of their materials. Proton exchange membrane fuel cells (PEMFCs), among the different types of FCs, have attracted the research interest especially for automobile applications. They have high-power density at low operating temperatures(less than 1000C), quick start-up and zero emissions. However, PEMFC systems still present certain drawbacks and improvements must be made in order to enhance their reliability for industrial applications. Cost reduction, durability, performance evaluation and reliability thus remain strong research issues. Mathematical modelling and simulation are needed to examine the behaviour and characteristics of FCs. These techniques can help in predicting and improving FCs' performance and reliability. There are several studies that have focused on the study and modelling of FC, among these studies, Guang (Guang et al., 2013), which presented the fundamental electrochemical and it also demonstrated the underlying electrochemical and transport mechanisms essential for PEMFC modelling. Chanpeng(Chanpeng 2011) used experimental and developed MatLab Simulink module to study the operation performance of 1.2KW PEMFC. (Tian 2009) proposed PEMFC mechanism modelling based on artificial intelligent to investigate PEMFC mechanism and faults. Tanrioven (Tanrioven and Alam 2006) presented a methodology for modelling and determining PEM characteristic mechanism to enhance its reliability. The Models play vital role to ensure the optimum design of FCs. This paper offers comprehensive study on the modelling and Simulink the operation mechanism of PEMFCs in order to investigate the reliability and performance of PEMFC under differ operating condition. Mathematical equations and modelling are used to define operating conditions and the performance of PEMFC.

The aim of this research is to develop a model for investigating the performance of a PEM fuel cell at different operation variables using semi-empirical equations. Model validation against the experimental data.

2. Fuel Cell System:

The basic structure of a PEMFC system as depicted in Figure (1) is composed of the following parts:

- **i- Electrolyser**: device that uses to separate the distilled water to hydrogen and oxygen which are used as fuel of FC.
- **ii- Fuel Cell**: the main part of this system. FC is an electrochemical device which uses the chemical energy to produce electrical energy.
- **iii- DC/DC converter**: device that works to control the output voltage (buck or boost converter).
- **iv- DC/AC inverter**: the main task of this device is to convert the output voltage from D.C signal into A.C signal.

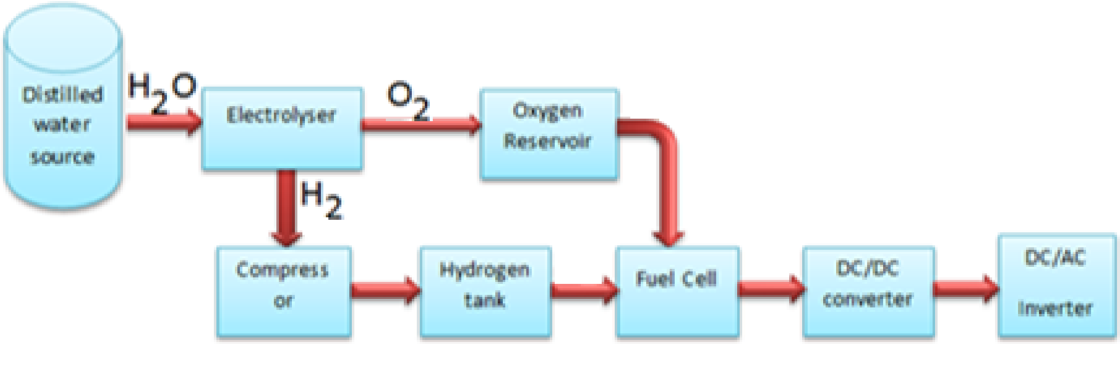

Fig.1 The schematic diagram of Fuel cell system

3. Electrolyser:

Hydrogen is one of the most promising alternative sources of energy for the future due to it has the capability of storing energy at high quality. For that, the hydrogen has been presented to become the cornerstone of future energy systems based on other renewable energy sources. Some of the researchers have been studied the uses of hydrogen as an energy carrier in storage and transport of energy.

Electrolyser is electrochemical device that uses electricity to decompose water into hydrogen and oxygen. When the voltage across the two electrodes (anode and cathode) exceeds the decomposition voltage of water (which is 1.23 V), the pure water will be separated into hydrogen and oxygen a. Equation (1) demonstrates the chemical reactions in electrolyser at both anode and cathode side:

$$at\ Anode\ side\ :\ 2H_2O \rightarrow 4H^+ + 4e^- + O_2$$

$$at\ Cathode\ side :\ 4H^+ + 4e^- \rightarrow 2H_2$$

$$Total\ reaction\ :\ 2H_2O \rightarrow 2H_2 + O_2 \text{Eq. (1)}$$

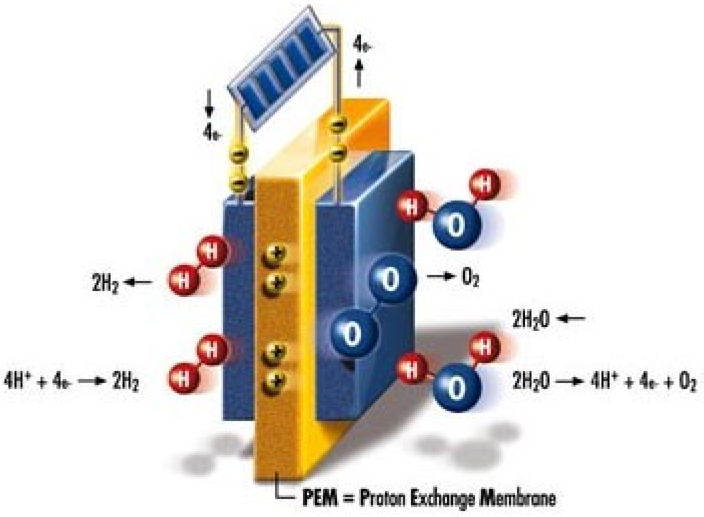

Fig .2 the functionality of the electrolyser (HTE 2012)

Electrical energy is need to achieving the previous equation. In addition to the electrolyser device, hydrogen may extract from natural gas as depicted in figure 3.

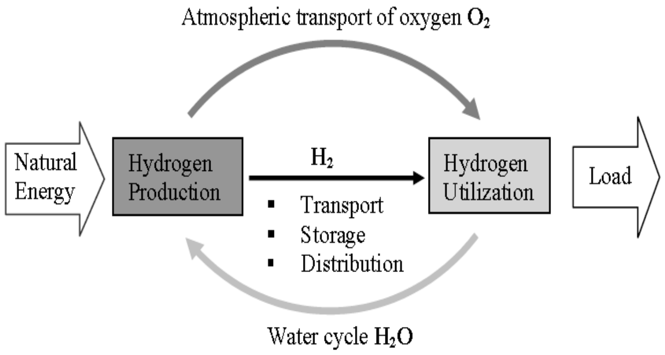

Fig.3 The natural energy hydrogen cycle

There are many methods used to conversion the hydrogen energy to electrical energy. Fuel cell has many advantages such as high conversion efficiencies that make it best way for hydrogen conversion.

4. The Operation Principle of the FC:

The operation mechanism of PEMFC will be investigated in order to illustrate the operation principle of FCs. The idea of operation depends on the presence of a Membrane separator (the Electrolyte) and the catalyst which is usually made of platinum powder and coating the carbon paper or cloth with a very thin layer (Dokkar 2011). The side of the plate is coated by the platinum is placed next to proton exchange membrane. Upon entering the hydrogen H_2 to the cell, the platinum works on separating it into proton and an electron. The membrane separator allows protons to pass and does not allow electrons. Therefore, electrons have to pass only through the current collectors, and this produces DC electrical current. In the opposite side of the membrane (i.e., at the cathode side) the electron binds with the proton in the presence of a catalyst again and with the presence of oxygen, the water H_2O is produced and heat spreads as shown in Figure 4.

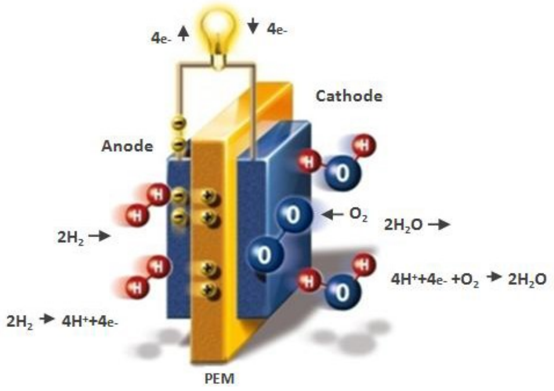

Fig .4 the functionality of the PEMFC (HTE 2012)

Table. Error! Reference source not found. **Types of FCs and their characteristics and usages**

Fuel Cell Type	**Common Electrolyte**	**Operating Temperature**	**Typical Stack Size**	**Efficiency**	**Applications**
Proton Exchange Membrane (PEM)	Perfluoro sulfonic acid.	50 - 100°C Typically 80°C	< 1kW– 100kW	60% transportation 35% stationary	• Backup power • Portable power • Distributed generation • Highway transportation • Specialty vehicles
Alkaline (AFC)	Aqueous solution of potassium hydroxide soaked in a matrix.	25 - 75°C	10 – 100 kW	60%	• Military • Space • Supermarkets • Hospitals • Hotels
Phosphoric Acid (PAFC)	Phosphoric acid soaked in a matrix	150 - 200°C	400 kW 100 kW module	40%	• Distributed generation
Molten Carbonate (MCFC)	Solution of lithium, sodium, and/or potassium carbonates, soaked in a matrix	600 - 700°C	300 kW-3 MW 300 kW module	50%	• Electric utility • Distributed generation
Solid Oxide (SOFC)	Yttria stabilized zirconia	700 - 1000°C	1 kW – 2 MW	60%	• Auxiliary power • Electric utility • Distributed generation

5. PEMFC Proton Exchange Membrane

5.1 Proton Exchange Membrane Fuel celles (PEMFCs):

The two scientists L. Niedrach and T. Grubb invented proton exchange membrane in 1960 in General Electric Company. PEMFC is the most common used fuel cell type; it is used in various fields due to its small size and its low temperature operation. PEMFC uses a polymer as membrane (Nafion), which plays the role of mediator in the electrochemical cell, in a solid state and thus it reduces the reaction temperature and increases the efficiency (speed of interaction in the start-up and responding when loading). The polymer separation membrane positioned between two electrodes of perforated platinum and it causes no risk of pollution due to the solid nature. Interaction takes place under the temperature of 80^0C and when the membrane exposed to water, it becomes conductive material for ions(Yan, Fan et al. 2012). The electrodes are made of platinum. The efficiency of such cells is up to 45-50% and their power density is high compared with other types of cells where up to 350-600 mW/cm^2 and the reactions are defined in Equation 2.

$$at\ Anode:\ 2H_2 \rightarrow 2H^+ + 4e^- \quad Eq.2a$$

$$at\ Cathode:\ O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \quad Eq.2\ b$$

$$at\ Cell:\ 2H_2 + O_2 \rightarrow 2H_2O + electricity + heat \quad Eq.2c$$

Another type of polymeric cells runs on methane gas directly, and it differs from the first type in terms of the electrode's materials. These cells have a device for the preparation of fuel, where it works on the saturation of methane with hydrogen. The problem in this type is the crossing of methane from the membrane and there is currently a lot of research to address this issue.

6. Polarization phenomenon:

When the FC is loaded, the voltage goes down by 60% or 70% of the open circuit voltage (because of the phenomenon of polarization as shown in figure.5). Both the output voltage and current density determine the characteristic of V-I curve. The output voltage of PEMFC is closely related with thermodynamically predicted in FCs and three major losses that are Activation losses, Ohmic losses, and Concentration losses. Activation losses occur due to electrochemical reaction. Ohmic losses occur due to ionic electronic condition. Concentration losses are produced due to mass transport.(Chanpeng 2011, Zheng 2013).

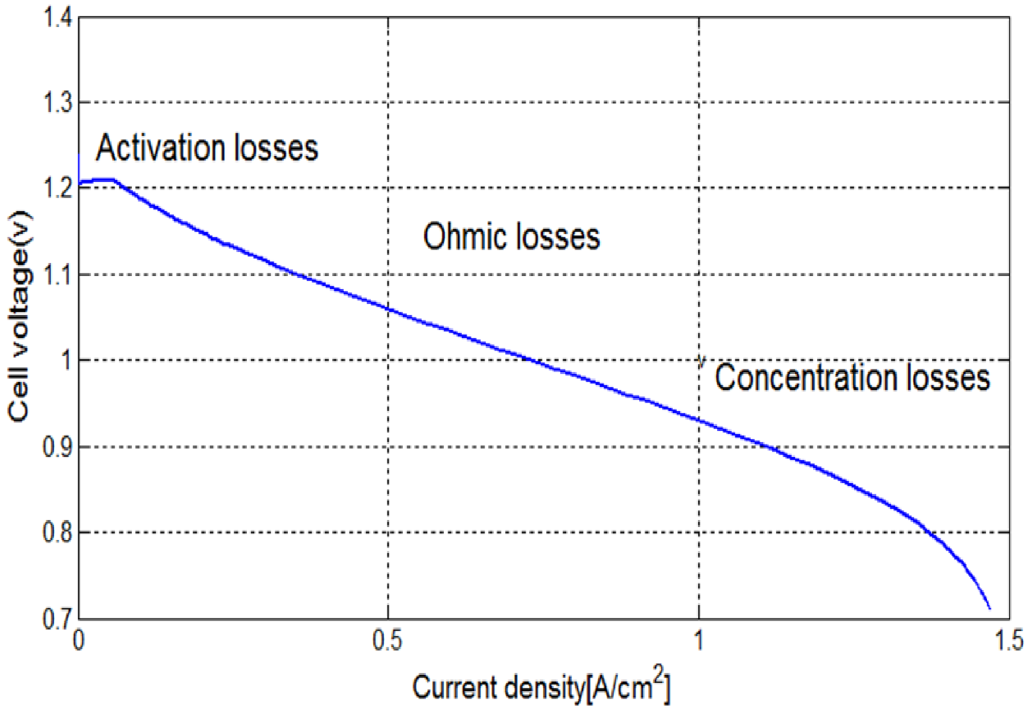

Fig.5 The schematic diagram of the FC through the production cycle and three losses.

6.1.1Activation polarization η_{act}:

When the cell is loaded, the voltage drops suddenly by (η_{act}> 50-100 mv) and then remains constant; because of the energy needed to trigger the interaction between gases and oxygen in particular. This drop is linked to the amount of catalysts and density of hydrogen and oxygen on the surface of the catalyst. The polarization equation is given by the following expression:

$$\eta_{act} = -0.9514 + T * 0.00312 + T * 7.4 * 10^{-5}[\ln(c * o_2] - 0.000187 * \ln(i) \;\; Eq.3$$

$$C * O_2 = \frac{P_{O2}}{5.08*10^{6}\, EXP\left(\frac{-498}{T}\right)} Eq.4$$

Where i is the density of current and C^*O_2 is the density of the hydrogen on the catalyst.

6.1.2 Ohmic polarization:

The ohmic polarization ($\boldsymbol{\eta ohm}$) is positively proportional to the current. Since the cell's resistance almost constant, the ohmic polarization changes linearly and this is because of the emergence of resistance while crossing of ions in the electrolyte and ohmic resistance electrodes (Dihrab, Sopian et al. 2009). The reduction of these resistances by using the appropriate electrolyte and metals in the electrodes can be adopted to overcome this problem, and the equation can be written as follows:

$$\eta \mathrm{ohm} = \mathrm{i}R^{internal} \quad \mathrm{Eq.}\,5$$

Where i represent the current of the cell and $R_{internal}$ is the internal resistance of the cell, and is given in the data sheet of the cell or calculated from the following relationship:

$$R^{internal} = 0.01605 - 3.5 * 10^{-5}.T + 8.0 * 10^{-5} * i \qquad \mathrm{Eq.}\,6$$

6.2.3Concentration Polarization:

This polarization occurs at high current densities due to lack of gases required for the reaction at the electrodes and that causes drop in the cell's voltage, which is calculated from the following relationship:

$$\eta_{con} = -\beta * \ln\left(1 - \frac{I}{I_{max}}\right) \quad Eq.7$$

$$\beta = 0.016$$

$$I_{max} = 1.5A/Cm^2$$

Where β is the cell's constant and (I) is the current density of the cell, I_{max} is the maximum current density and its value between 1 and 1.5 per centimetre square, and the equation of the final voltage of the cell becomes:

$$V = E - \eta_{act} - \eta_{ohm} - \eta_{con} \text{ Eq.8}$$

$$V = \Big(1.23 - 0.9 * 10^{-3}(T - 298) + \frac{RT}{4F}(\ln(P^2H_2 * PO_2))$$
$$- \big[-0.9514 + T * 0.00312 + T * 7.4 * 10^{-5}[\ln(C * O_2)] - 0.000187 * \ln(i)$$
$$+ (-i * (0.01605 * 10^{-5}) * -3.5 * T + 8.0 * 10^{-5} * i)\Big)$$
$$- \left(-\beta * \ln\left(1 - \frac{I}{I_{max}}\right)\right)\big] \text{ Eq. 9}$$

6.3 Heat and Temperature Management:

When modelling or designing FCs stake, the heat management must be taken into account to ensure that the FC will work at the desired temperature. The management of heat is significantly related to FC’s performance. The amount of waste heat in FC equivalent almost its electric power produced leads to reduce the efficiency around 50%.

6.4 Output Power of the FC :

The capacity of the FC can be obtained from the following equation where I is the current density per centimetre squared in the pole of the cell. A is the electrode surface, and V is the voltage of the cell and these values are given in the datasheet of the cell.

$$P = V * I * A \quad \text{Eq. 10}$$

7. FC’s Modelling:

To improve the system's performance, design optimisation and analysis of FC systems are important. Modelling and simulation are needed as tools for design optimization of FCs, stacks and FCs power systems. The performance of FC during operation depending on the final equation 9, obtained by the integration of the equations 5 to 8. The advantage of the final equation is that it is less influenced by the determinants of mechanical and physical components of the cell and this equation relies on constants, temperature, operating, and pressure of the gases involved and the current density and voltage FC. The final equation has been represented in the environment MatLab to show the electrical performance of the cell and the impact of gases' pressure and temperature on the cell.

7.1 Voltage / Power Relationship Curve:

Figure 6 shows the relationship between the output voltage of the cell, power density with current density under the operation conditions given in the cell's data sheet such as temperature and pressure (346 K & 3 bar), and the results are similar to the curves in the scientific literature for FCs .This curve is the true measure of the performance of the cell and the conclusion of voltage and current work and the maximum power that can be produced without damaging the cell during the investigation of the effect of pressure and temperature, which will be addressed in the subsequent paragraphs in detail.

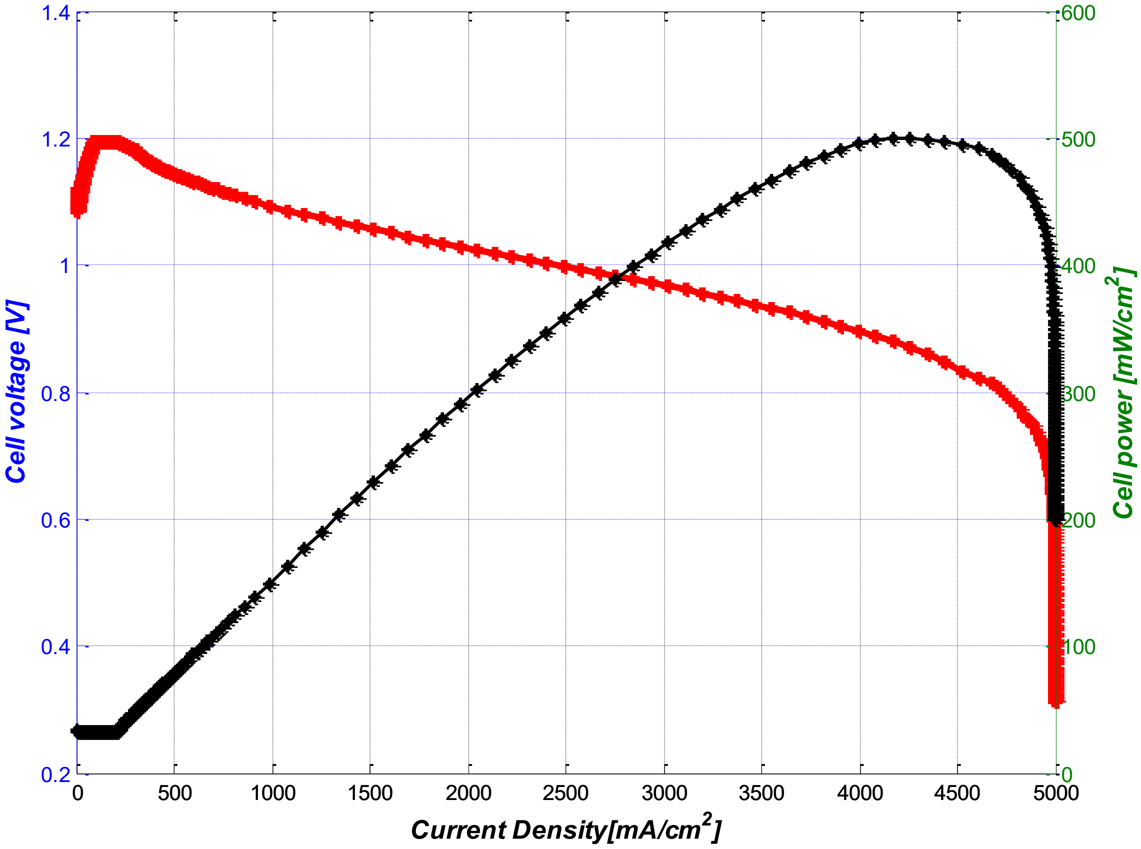

Fig.6 Relationship between voltage, power density and current density

7.2 Power Density Curve:

Figure 7 shows the power density against the current density. When the power density increased, the current density rises and then the power density it go down because of the increasing polarization affecting the cell's voltage. Usually the highest point of the curve is not the point of the operation for the cell (i.e., the cell cannot operate at the maximum power because of that cell outcome becomes low). At this point, the water increase and the temperature rises; making it difficult for the driving/ controlling the cell and shorten its useful life.

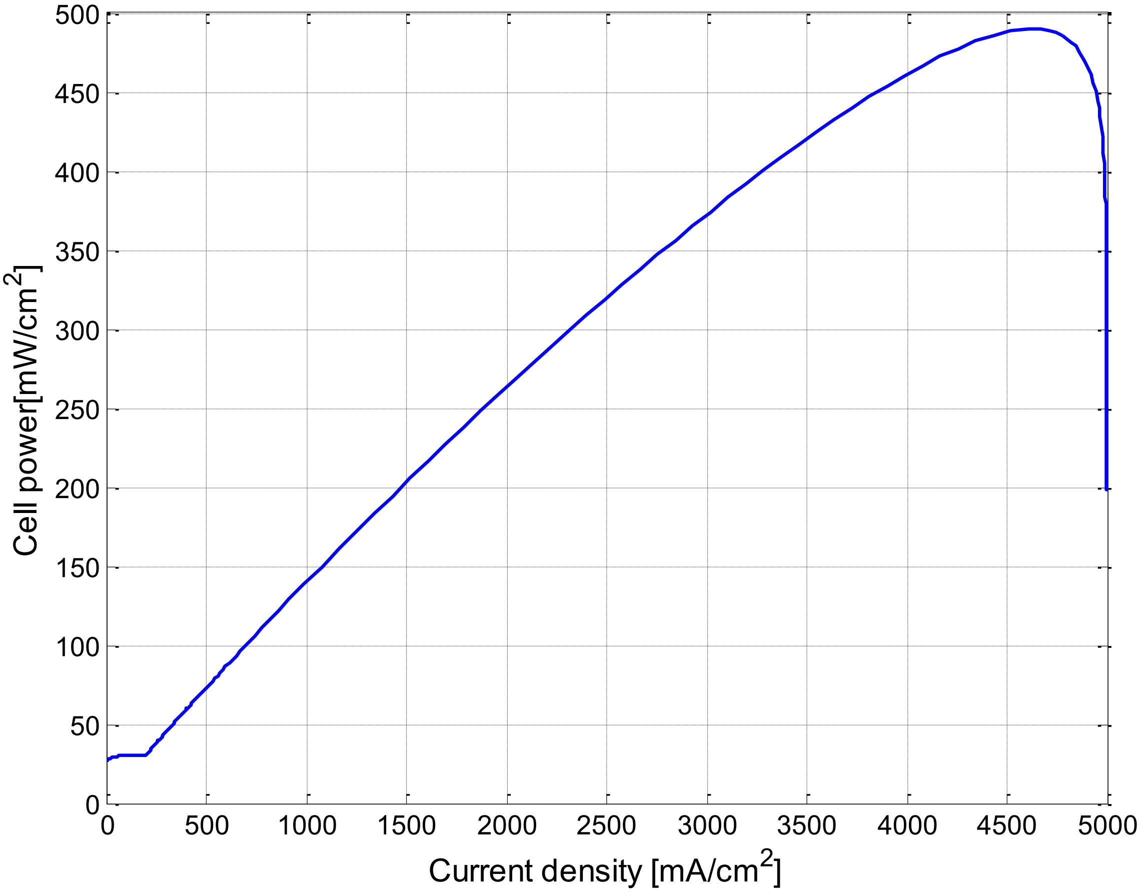

Fig.7 Relationship between power and current density

7.3 The Effect of Pressure and Temperature on the Polarization Curve and Power Density:

Figure 8 shows the polarization curve of the FC for two cases of operation:

The first case of works under the conditions of the cell such as temperature and pressure (353 K &3 bar). The second case of operation is within the statutory requirement (323K &1.5 bar), which shows the decline in output cell. polymeric FCs typically operate at a temperature of $70\text{-}90^{O}$ C and atmospheric pressure (1.5-3.5 bar) as the cell then gives its highest outcome. Therefore, Figure 6 shows at low temperature and pressure, the voltage declines 0.1 V, and it causes the decline in the outcome by 10 % of its nominal output.

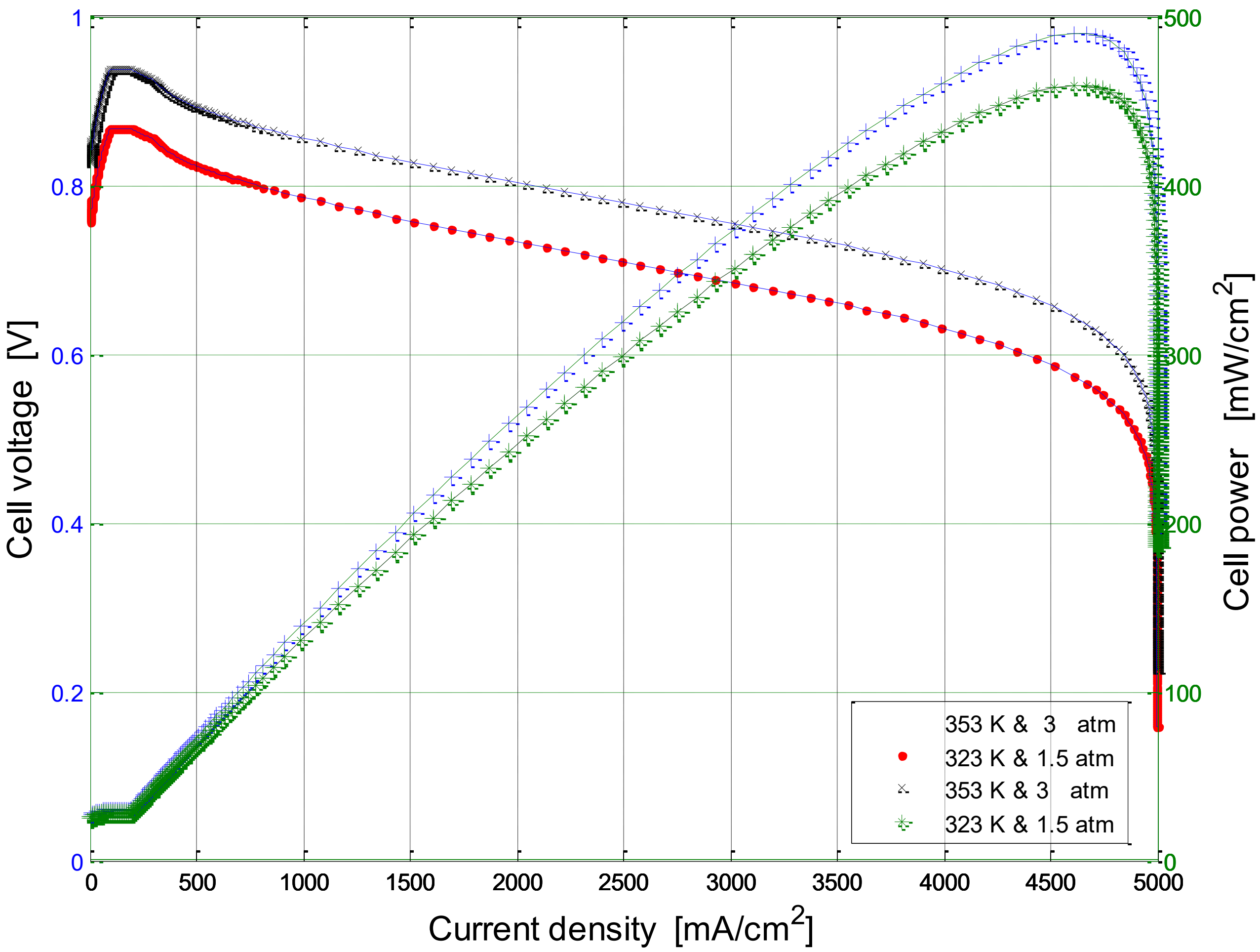

Fig. 8 Relationship between current and power density with voltage under different operation conditions

7.4 Polarization Curve of the Cell

Figure 9 shows the voltage of the open circuit cell E and stages of falling the voltage in the FC during operation. Owing to decline resulting from the polarization of the three (activation η_{act} and Ohmic η_{ohm} and focus η_{con}), as the Figure l shows that the cell's voltage at start-up lands in sudden, and due to the activation of η_{act} and then decline until at least this is almost disappears.The second decline in the voltage is caused by the internal resistance of the cell η_{ohm} because of the of resistance of the ions while crossing in the electrolyte and resistance ohmic electrodes and rise linearly with increasing load current. Third decline in voltage η_{con}

happens at ~~the~~ high current densities and because of the non-arrival of reaction gases to the electrodes sufficiently, as shown in the Figure, the activation losses and the ohmic decline at low current density is the dominant and most obvious (Al-Dabbagh 2010, Dokkar 2011).

Note: In Figure 7, letter E is used instead of η to indicate polarization.

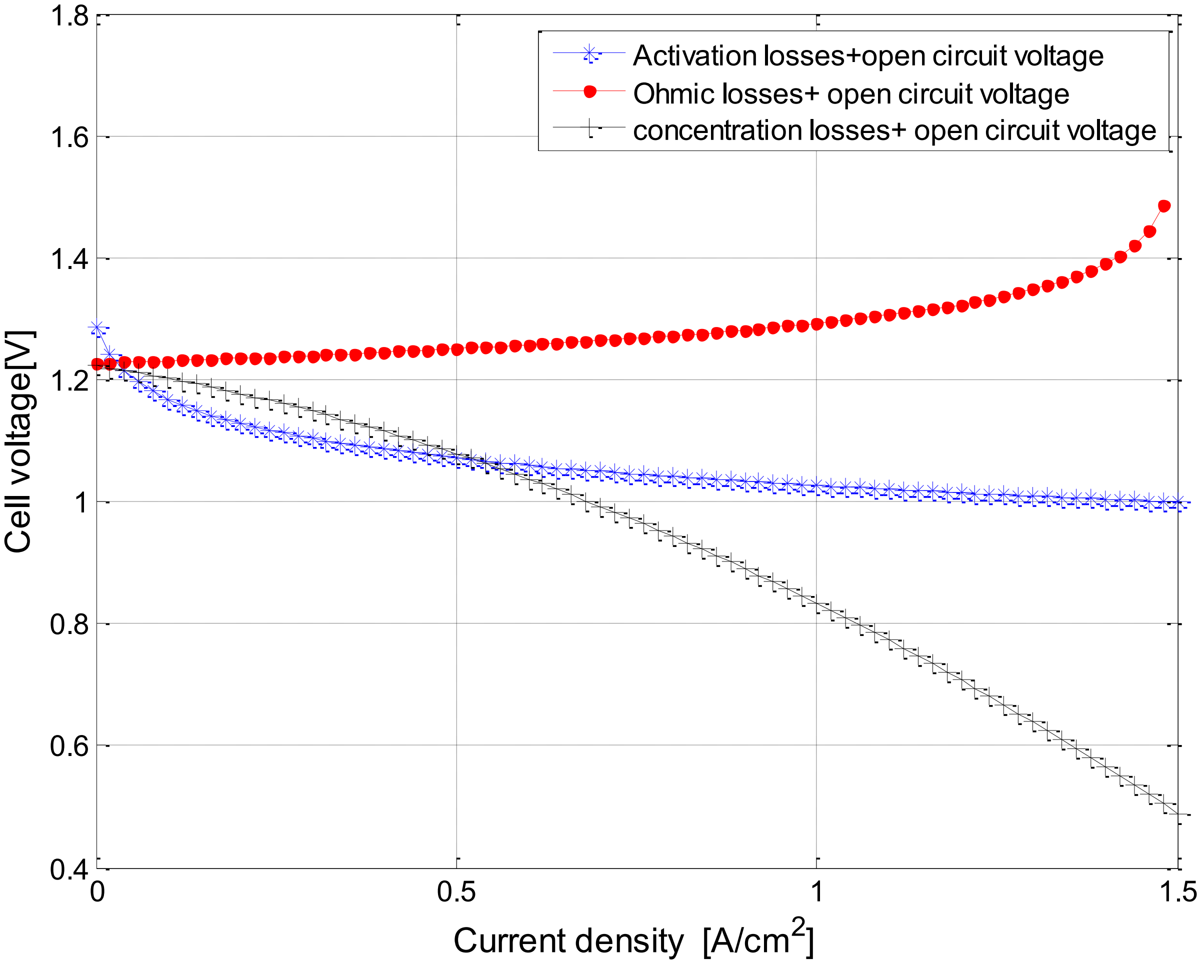

Fig.9 Losses in FC (activation losses, Ohmic losses and concentration losses)

7.5 Impact of Pressure on FC Voltage:

Figure 10 shows the improvement of the performance of the polymeric FC when the pressure increases. However, this increase must be within the allowable pressure in the datasheet of the cell because the increased pressure on the nominal value of 3 bar will improves performance slightly, where the values of the cell converge when voltage increased pressure more, and this is illustrated by the convergence of the lines in Figure 8, but this increase leads to higher temperatures and values of the three polarizations where its negative impact will be more positive and this causes the decline in outcome and increase the cost of production.

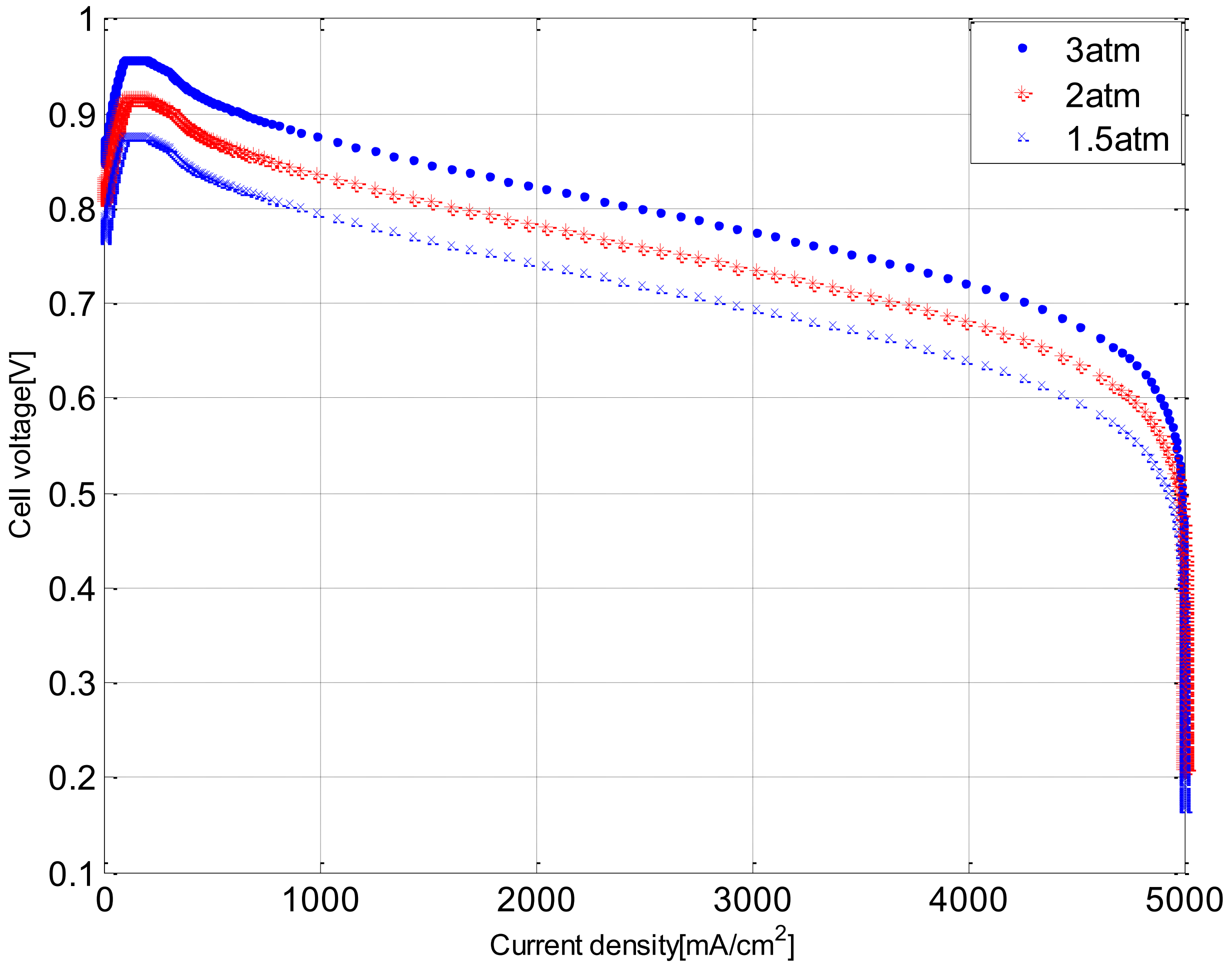

Fig. 10 Influence of gases pressure on performance of FC

7.6 The Impact of temperature on FC voltage:

Figure 11 shows that the increase in the temperature improves the performance of the cell, causing a decline of the voltage which leads to the reduction of voltage dropping factors and in particular the decline in the activation and increase the overall outcome of the cell, but under the conditions of operation, in order to prevent the loss of moisture needed for the cell membrane. Usually the temperature of the polymeric FC do not exceed 95^{O}C.

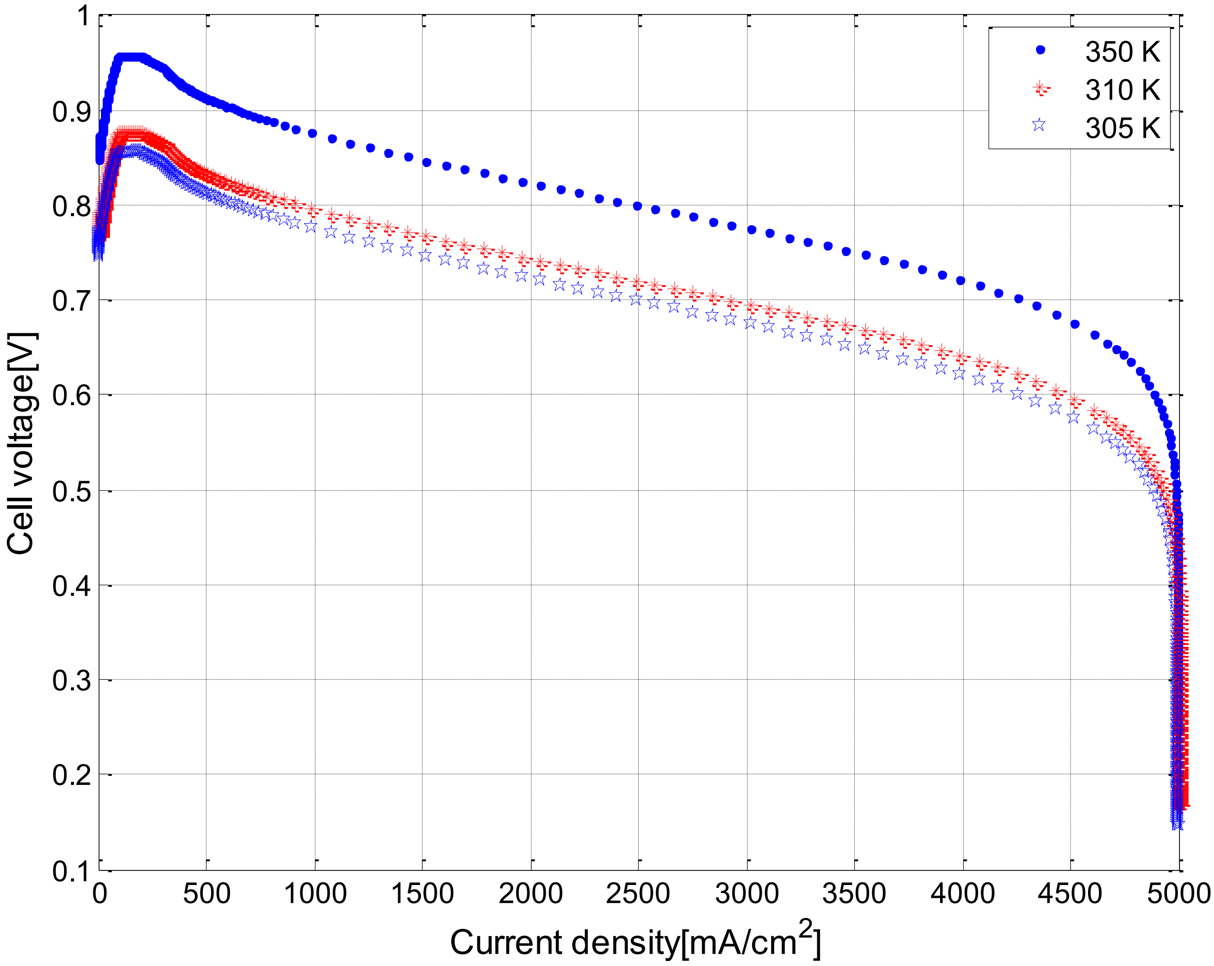

Fig. 11 Influence of temperature on performance of FC

7.7 Operating Voltage for FC

Figure 12 shows the curve of power density vs FC voltage. it is possible to obtain higher power at voltage of 0.6-0.8 V and this voltage is the operation voltage of a FC, and as noted earlier, it is important to find a balance between maximum power produced by the cell and the determinants such as operating pressure and heat allowed for the cell in order to not to adversely affect the cell's life and performance over time.

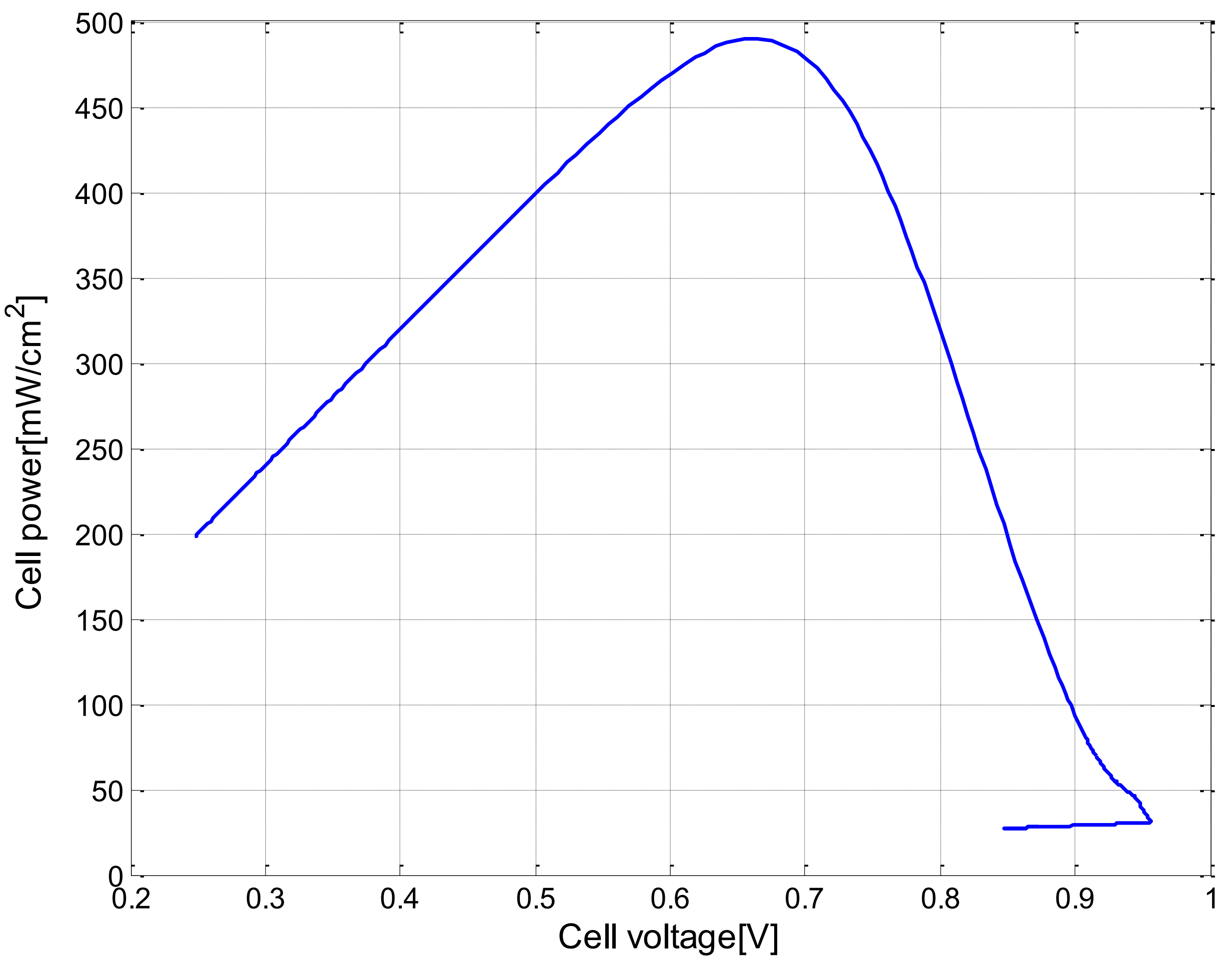

Fig. 12 Relationship between power density and voltage

8. Experiment apparatus:

In order to determine to voltage current characteristic of PEM and to validated the modeling results, several experiments have been made in MMU labs using PEMFC system. Table 2 listed the values that have been collected form 500 mw FC unit for various load (resistance) values setup. Figure .13 and figure 14 show the polarization curve and output power vs current density respectively for real data gathered from experiments.

Table 2 data collected form 500 mW PEMFC unite

Load(Ω)	Voltage(V)	Current (A)	Power (mw)
0	0.24	1.61	386.4
0.1	0.32	1.43	457.6
0.33	0.47	1.05	493.5
1	0.62	0.56	347.2
3.3	0.76	0.22	167.2
10	0.84	0.08	67.2
33	0.90	0.03	27
100	0.94	0.01	9.4
330	0.97	0.01	9.7
∞	1.1	0	0

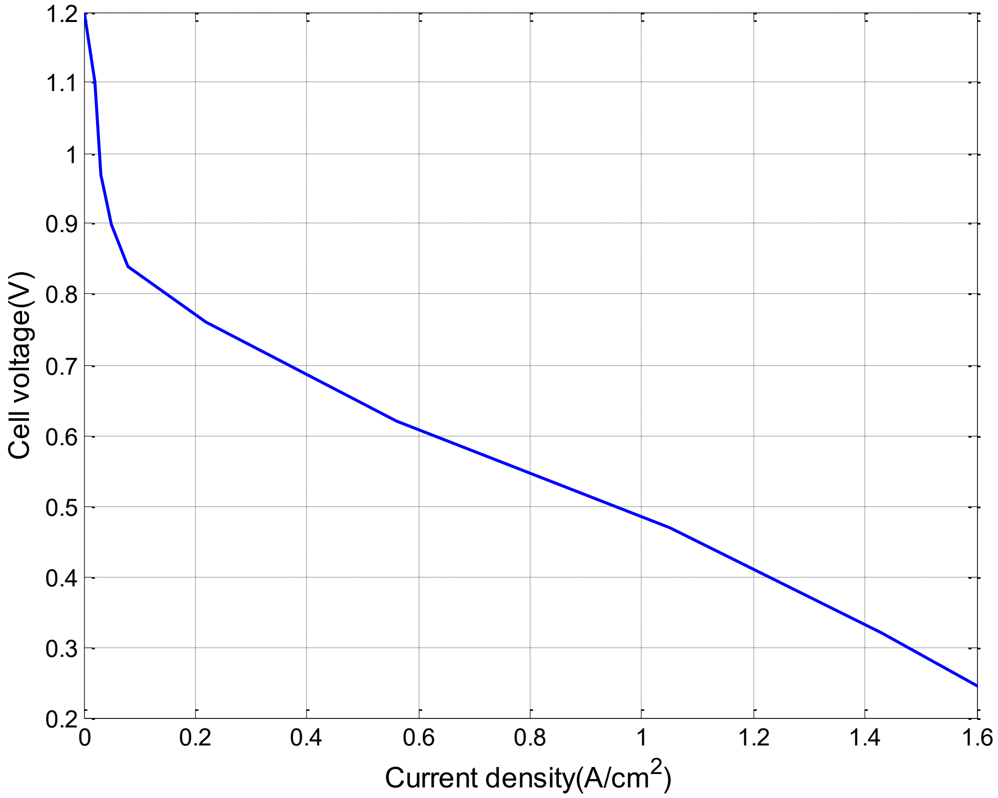

Fig. 13 polarization curve obtained from real data

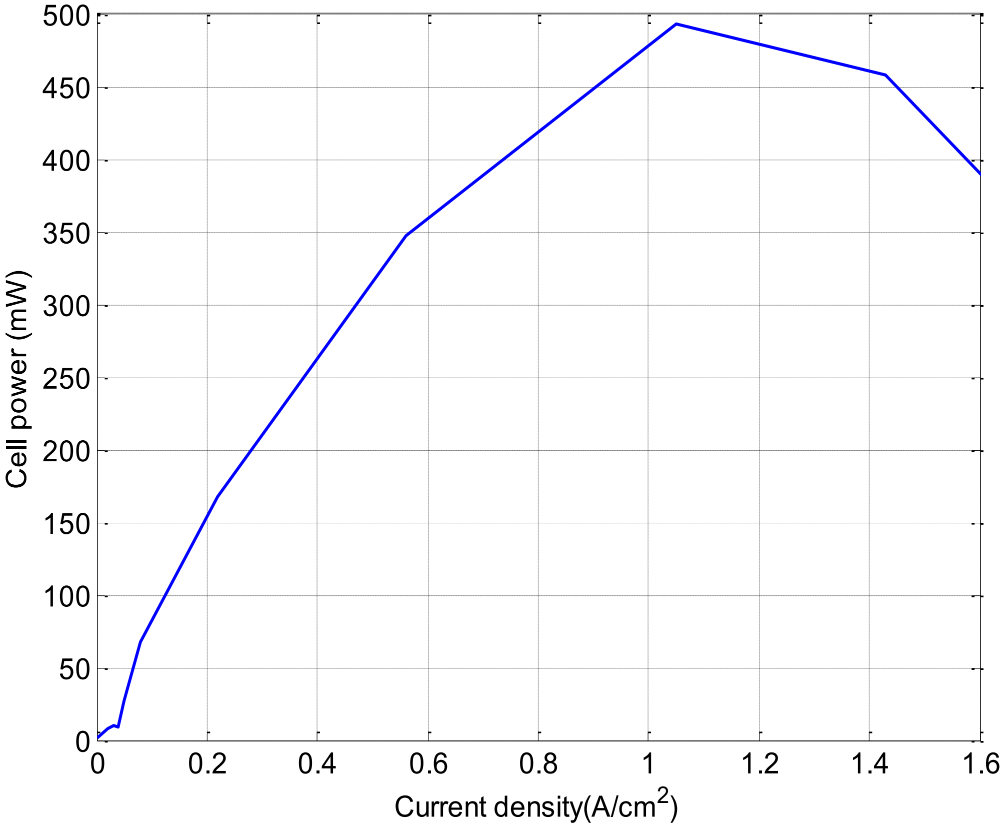

Fig. 14 output power vs current density

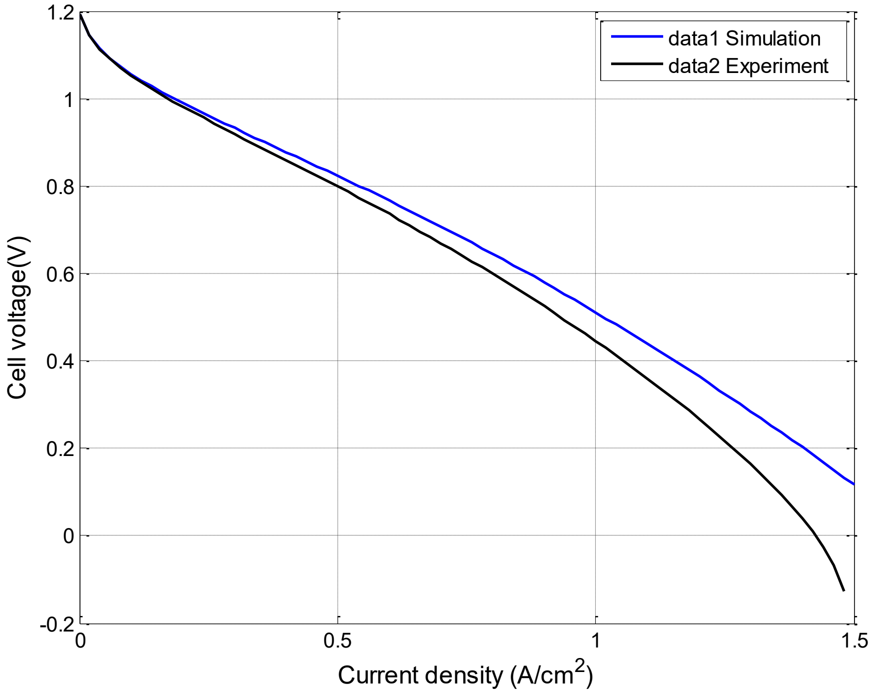

Fig. 15 V-I curve for simulation and experiment results

9.Conclusions:

This paper presented a realistic PEMFC dynamic model to allow better understanding the operating parameters effects. The impact of gases' heat and pressure interaction and the current density on the output voltage the cell and power density , have been analysis to determine the overall performance of the PEMFC. Mathematical and simulation model has been developed in order to study the behaviour of the PEMFC under various operations. Where it is possible to exploit this model to analyse in detail the impact of the changes on cell behaviour, such as temperature, pressure and load change. We have also modelled these equations using the MatLab environment and got curves to describe the impact of each case, these curves enables us to more understanding the FCs and avoiding the factors that reduce the performance and reliability of the cell. A set of lab experiments have been conducted to validate the model results.

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