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Experimental investigation of operating parameters and control the performance of a PEM fuel cell

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Abstract
In this study, the performance of a PEM fuel cell is investigated experimentally. Some parameters such as input oxygen temperature (T_{O2}), input hydrogen temperature (T_{H2}), cell temperature (T_{cell}), input pressure (P), oxygen flow rate ($\dot{m}_{O2}$) and hydrogen flow rate ($\dot{m}_{H2}$) affect the performance of the cell. A series of experiments are carried out to investigate the influence of the above parameters on the polarization curve under the normal conditions. A PEM fuel cell with $25cm^2$ active area and Nafion 117 membrane for the anode and cathode is employed as a membrane electrode assembly. The results show that increase in the operating temperature of the cell and inlet gases and pressure can enhance the cell performance. Also the results show that when the oxygen flow rate is at 0.9 L/min and the hydrogen flow rate is at 0.5 L/min the performance of the cell increases.

Keywords: Fuel cell; Rectangular channel; Flow rate; Performance; Operating parameters.

1. Introduction

Proton exchange membrane fuel cells (PEMFCs) represent a viable alternative power source for various applications. However, to satisfy the requirements for compactness, low cost, high power density, performance and stability, various aspects of the PEMFC must be optimized. Among the various fuel cell types, the proton exchange membrane (PEM) fuel cell is drawing more attention due to its low operating temperature, ease of start-up and shut-down and compactness. Furthermore, the PEM fuel cell is being investigated as an alternate power generation system especially for distributed generation and transportation. The PEM fuel cell is providing reliable power at steady state; however, it is not able to respond promptly to a load step change. Since the fuel cell is an electrochemical energy conversion device that converts fuel into electricity, its dynamic behavior depends both on chemical and thermodynamic processes [1]. The polymer electrolytes work at low temperature, which brings this further advantage that a PEM fuel cell can start quickly. PEM fuel cells are being actively developed for use in cars and buses, as well as for a very wide range of portable applications, and also for combined heat and power systems.

In the present work, the effects of oxygen and hydrogen temperature, cell temperature, input pressure and oxygen and hydrogen flow rate on the performance of a rectangular channel geometry PEM fuel cell have been studied experimentally. Several polarization curves have been obtained in different conditions, displaying the trend of the cell voltage against current. The experimental design, based on design of experiments techniques, studied the effect of the main operation factors (temperature, pressure, gas flow) at different levels of power load. The objective of this paper is to analyze the influence of different operation factors on the voltage (and consequently the electric power) supplied to a PEM fuel cell at different levels of cell current.

2. Previous works

Amphlett et al. [2, 3] investigated a theoretical model which was employed to provide the structure of the equations, and then, the parameters of these equations were found by using the regression techniques to fit the experimental results. Also they studied a semi-empirical model with a theoretical background that takes into account the main variables of the fuel cell operation such as the operating temperature, the partial pressures at the electrodes and the fuel cell current.

Del Real et al. [4] investigated a simple empirical equation to model the fuel cell voltage with considering the variations of the main process variables. The model equation has 11 parameters: one parameter related to the mass of liquid water at the anode channel must be estimated due to technical constraints, and the other parameters are obtained from experimental data. Although the model proposed by them, fitted well with the experimental data, the equation of the fuel cell voltage does not have a theoretical basis, and, therefore, it is based on assumptions relating to the effects of temperature and partial pressures that are not proven to be general for fuel cells other than those used in [4].

Scrivano et al. [5] presented the results of an experimental analysis performed on an Exchange miniaturized, 6W Proton Membrane Fuel Cell (PEMFC) system, integrated with on-site hydrogen production by electrolysis; in particular, they investigated the effects of environmental parameters such as the external temperature and the humidity on the performance of fuel cells. Also they proposed a simple semi-empirical mathematical model capable to perform rough prediction on the behavior of such systems when exposed at different ambient temperatures. The model threats the stacks as black boxes, not investigating singularly the inner phenomena which occur in the cell.

Berning and Djilali [6] using a three-dimensional computational model for a single cell with an active area of $25cm^2$ and single-serpentine flow field, investigated the influence of this parameter on the cell performance.

Yi and Nguyen [7], used the numerical methods to solve a two-dimensional single-phase PEMFC model with interdigitated flow channels so as to evaluate the effects of inlet and exit pressures, gas diffusion layer thickness and carbon plate width on the performance of PEMFC.

3. Description of the experiments and method of the measurements

For experimental investigation of the performance of the fuel cell a setup has been fabricated. It allows controlling several physical parameters, and the measurement of many output data. In fact, the polymeric membrane has a permeability to hydrogen and oxygen; due to the high-pressure gradient from cathode to anode, this driving force could push hydrogen from cathode to anode across the membrane and a dangerous mix with oxygen could occur; this concentration must always be kept below a safety level.

The test bench is made up of four main subsystems. First, the gases supply system, which sends the oxygen and hydrogen flow into the system for electrochemical reaction. Second, there is two humidifier that humidify the oxygen and hydrogen before going into the cell for complete transferring of proton from the membrane to the cathode side. Third, the nitrogen supply system is applied to inert any flammable mix inside the ducts and to purge the system before activation. Finally, there is the electrical power supply, regulated from an AC/DC voltage regulator driven from the control panel.

The examined prototype can operate at a maximum 5 bar absolute pressure; a pressure regulator valve is included, to make possible to vary the operating pressure of the FC system and the accuracy of monitoring the pressure is $\pm 2\%$. Two flow meters is used to measure the flow rate of the oxygen and hydrogen that the accuracy of them is $\pm 0.1L/\min$.

In order to plot the polarization curve and simulate a variable load, a resistors box was used that the accuracy of monitoring the voltage and ampere is $\pm 1\%$. The resistors box, located outside the test chamber, is manually operated; the box and the cables do not introduce relevant errors because they are shielded from external magnetic fields (due to the very low current values). In order to operate in equilibrium conditions, current and voltage values corresponding to each particular value of the total resistance were measured after a sufficient time period to ensure stationary conditions to have been reached as concerns both fuel cell performance and the values of humidity and temperature in the test chamber. The temperature of the inlet gases was measured by digital thermometer with $\pm 0.1^{\circ}C$ accuracy.

A schematic of the test bench is presented in Figure 1.

The specifications of the test system for this study are:

- The humidifier system is membranous.
- The test bench has the system of announcement the leakage of hydrogen.
- The system can control and show the temperature of the oxygen and hydrogen.
- The system can control and show the temperature of the cell.
- The system can control and show the flow rate of the oxygen and hydrogen.
- The system can control and show the inlet pressure of the oxygen and hydrogen.
- The system can show the voltage of the cell.
- The system can show the current of the cell.

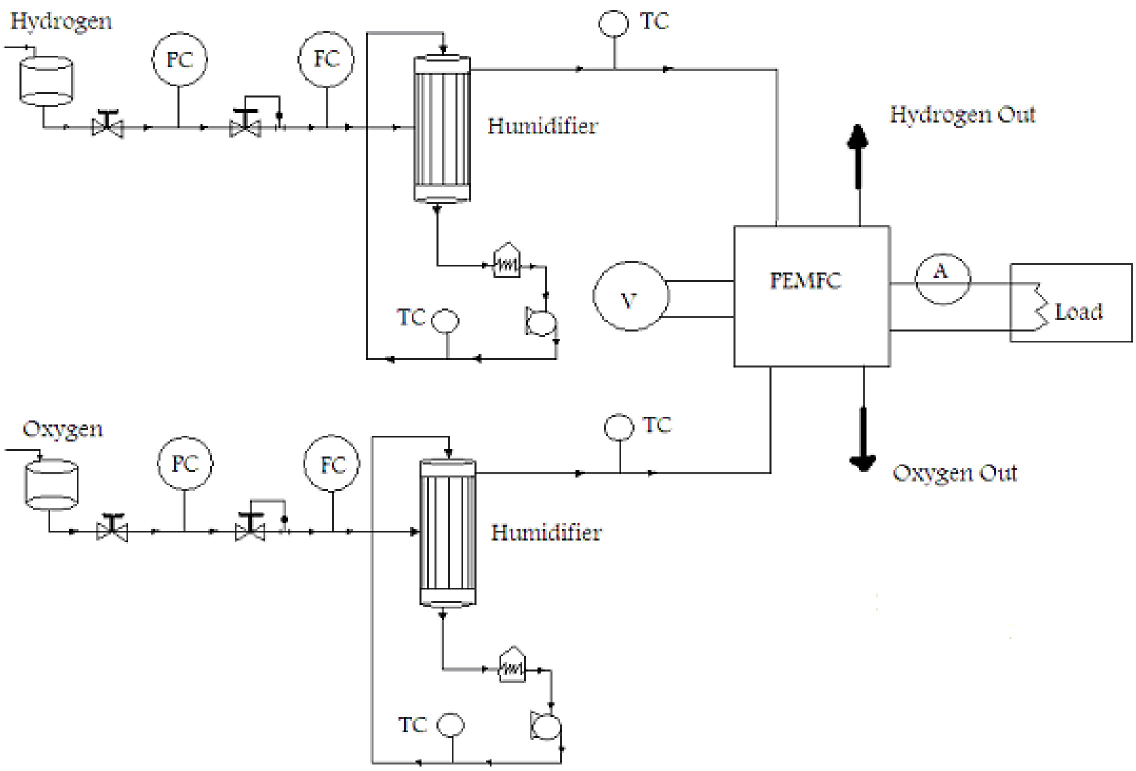

Figure 1. Schematic of the PEMFC system

Table 1 shows the environs of operation of the experimental setup in this study.

The PEM fuel cell considered in this study is a single cell with the size of $45 \times 95 \times 101 mm^2$ and an active area of $25cm^2$ and serpentine and rectangular flow field geometries of channels with the weight of 1300gr. The width, land width and depth of the channel were selected to be 1, 0.8 and 1mm respectively. For a bipolar plate, non-porous graphite is selected. A Nafion 117 membrane for the anode and cathode was employed as a membrane electrode assembly. On both sides of the MEA, there were 0.33mm thick carbon papers that acted as diffusion layers. The thickness of the catalyst layer and the proton exchange membrane is about 0.01mm and 0.051mm. The maximum output power of the cell is 11 watts at 0.6 cell voltage. The geometry of the channels of the cell in the experimental setup is shown in Figure 2.

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Table 1. Operational characteristics of the test bench

Voltage	0-2 V
Current	0-20 A
Power	0-22 W
Moisture	100 %
Flow rate	0-2 L/min
Gases temperature	Up to 75 $^{\circ}C$
Cell temperature	Up to 75 $^{\circ}C$

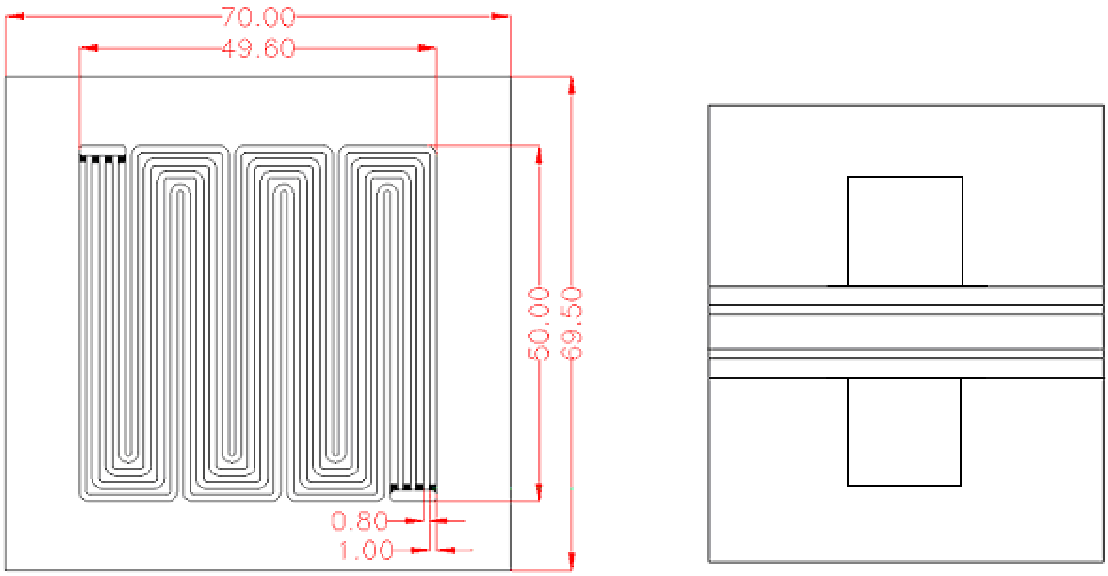

Figure 2. Schematic of the channels PEMFC

The changed parameters are: input oxygen temperature (T_{O2}), input hydrogen temperature (T_{H2}), cell temperature (T_{cell}), input pressure (P), oxygen flow rate ($\dot{m}_{O2}$) and hydrogen flow rate ($\dot{m}_{H2}$) and the measures parameters are voltage and current of the cell.

At first, we perform the experiments by humidifying the membrane of the fuel cell by saturation water vapor and then change the input oxygen temperature, input hydrogen temperature, cell temperature, input pressure, oxygen flow rate and hydrogen flow rate and measure the pointed parameters and the voltage and the current of the cell after steady state condition. Figure 3 shows the experimental setup.

4. Results and discussion

The main goal of this study is to investigate the effects of important parameters on the performance and polarization curve of the rectangular channel geometry PEM fuel cell. The Range of changing the parameters in this study is shown in Table 2 and the experiments for each of the parameters done and repeated while the steady state condition occurred.

Figure 4 illustrates the polarization curves of the PEM fuel cell to investigate the influence of the input pressure gases on the overall fuel cell performance at $T_{cell} = 60^{\circ} C$, $T_{O2} = 55^{\circ} C$, $T_{H2} = 55^{\circ} C$, $\dot{m}_{O2} = 0.5L/\min$ and $\dot{m}_{H2} = 0.3L/\min$. It is clear that an increase in pressure increases the performance of the fuel cell which is due to decrease of ohmic and concentration losses and increase more efficient fuel transport from the gas diffusion layers and the chemical reaction at the catalyst surfaces and exchange current density.

As can be seen, higher cell-operating pressure results in more even distribution of the local current density due to the high oxygen concentration at the catalyst layer. This leads to the fact that for a lower cell-operating pressure at a constant nominal current density, there is a much stronger distribution of current inside the cell, the maximum local current density being at the inlet under the channel area.

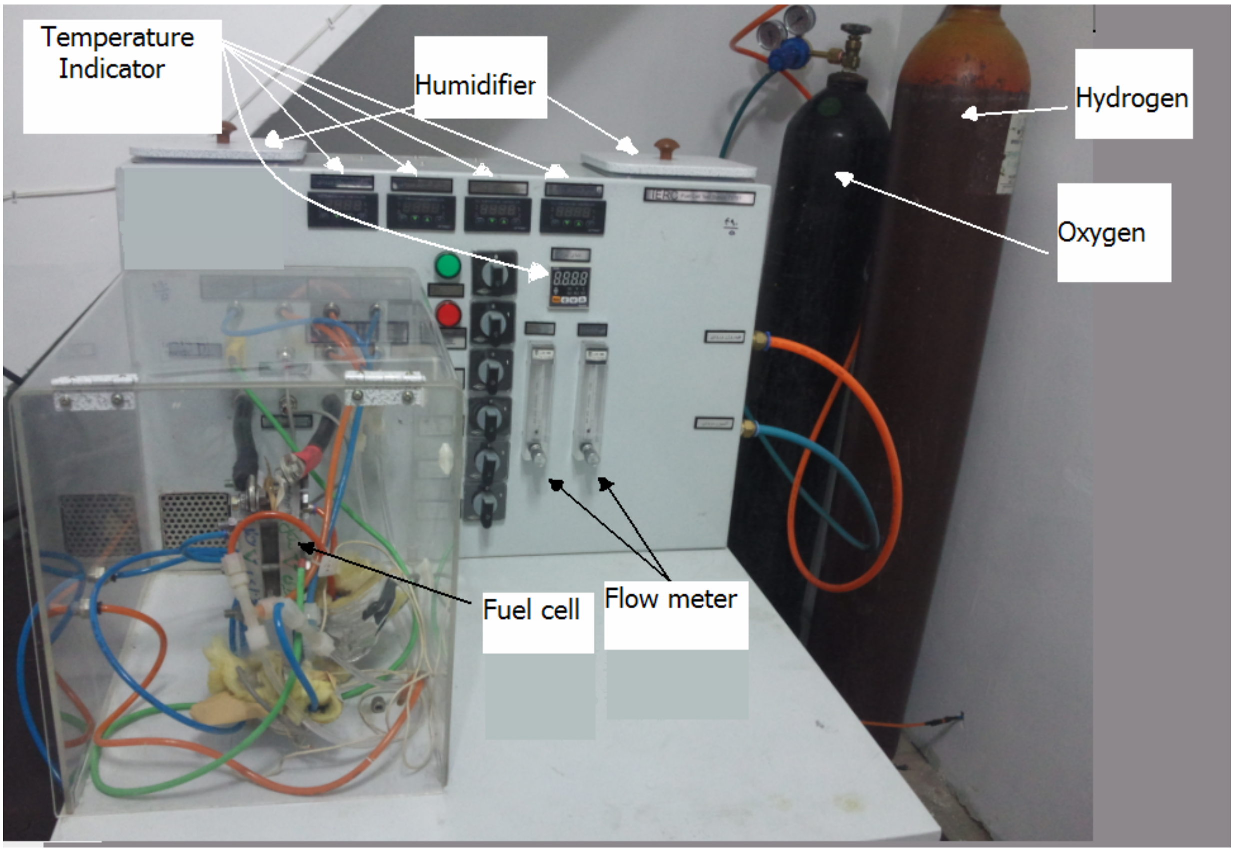

Figure 3. Schematic of the experimental setup

Table 2. Range of changing the parameters in this study

Description	Unit	Value
Oxygen flow rate	L/min	0.5-1.3
Hydrogen flow rate	L/min	0.3-1.1
Anode inlet pressure	Bar	1-4
Cathode inlet pressure	Bar	1-4
Cell temperature	$C°$	40-60
Oxygen temperature	$C°$	45-65
Hydrogen temperature	$C°$	40-60

In Figures 5 and 6 the effect of hydrogen flow rate and oxygen flow rate of the anode and cathode sides at the overall cell performance of the PEM fuel cell for $T_{cell} = 60^{\circ}C$, $T_{O2} = 55^{\circ}C$, $T_{H2} = 55^{\circ}C$, $\dot{m}_{O2} = 0.5L/\min$ and P=2.905 bar are shown. It is clear that by increasing the hydrogen flow rate from 0.3 L/min to 0.7 L/min and the oxygen flow rate from 0.5 L/min to 0.9 L/min the cell performance enhances but when the flow rate increases from 0.7 L/min to 0.9 L/min for hydrogen and from 0.9 L/min to 1.3 L/min the cell performance decreases. It is due to that by increasing the flow rate of hydrogen and oxygen more fuel and oxidizer transport from GDL to the catalyst layer and the electrochemical reaction enhances but when the flow rate of hydrogen and oxygen increase from 0.7 L/min and 0.9 L/min the transportation of fuel and oxidizer to the GDL decrease and they come out from the channel without an electrochemical reaction. Also it is clear that when $i \le 0.1A/cm^2$ for hydrogen and $i \le 0.05A/cm^2$ for oxygen the performance of the cell is better when the flow rate decreases.

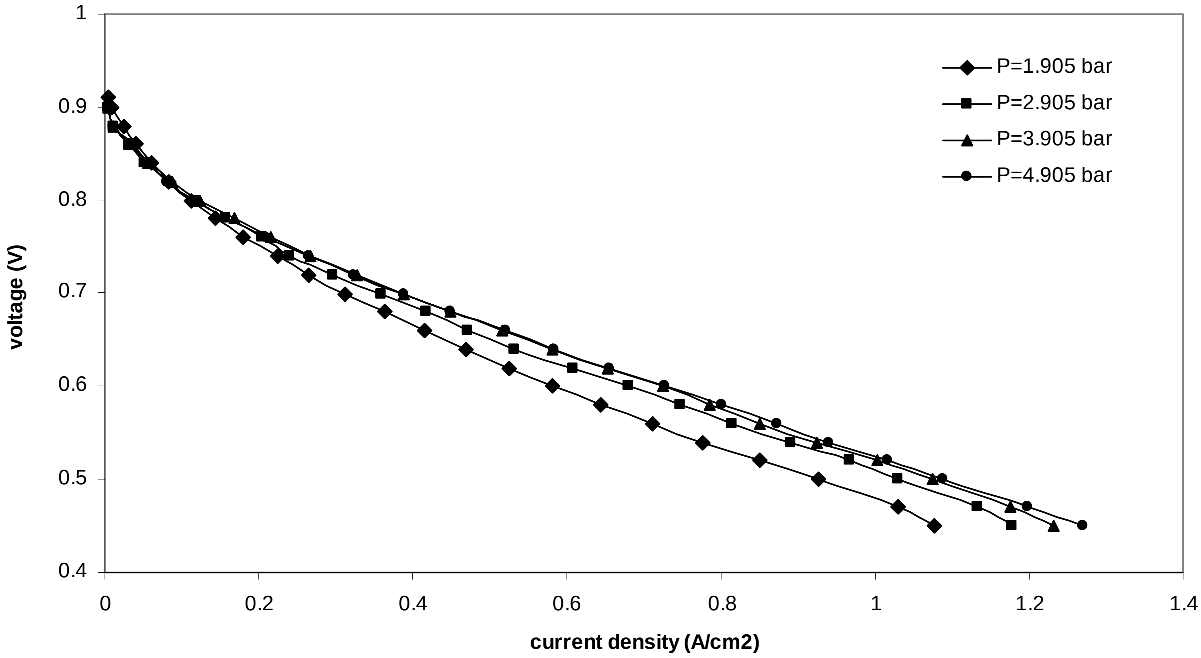

Figure 4. Variation of cell performance at different cell pressures for $T_{cell} = 60^{\circ}C$, $\dot{m}_{O2} = 0.5L/\min$, $\dot{m}_{H2} = 0.3L/\min$, $T_{O2} = 55^{\circ}C$ and $T_{H2} = 55^{\circ}C$

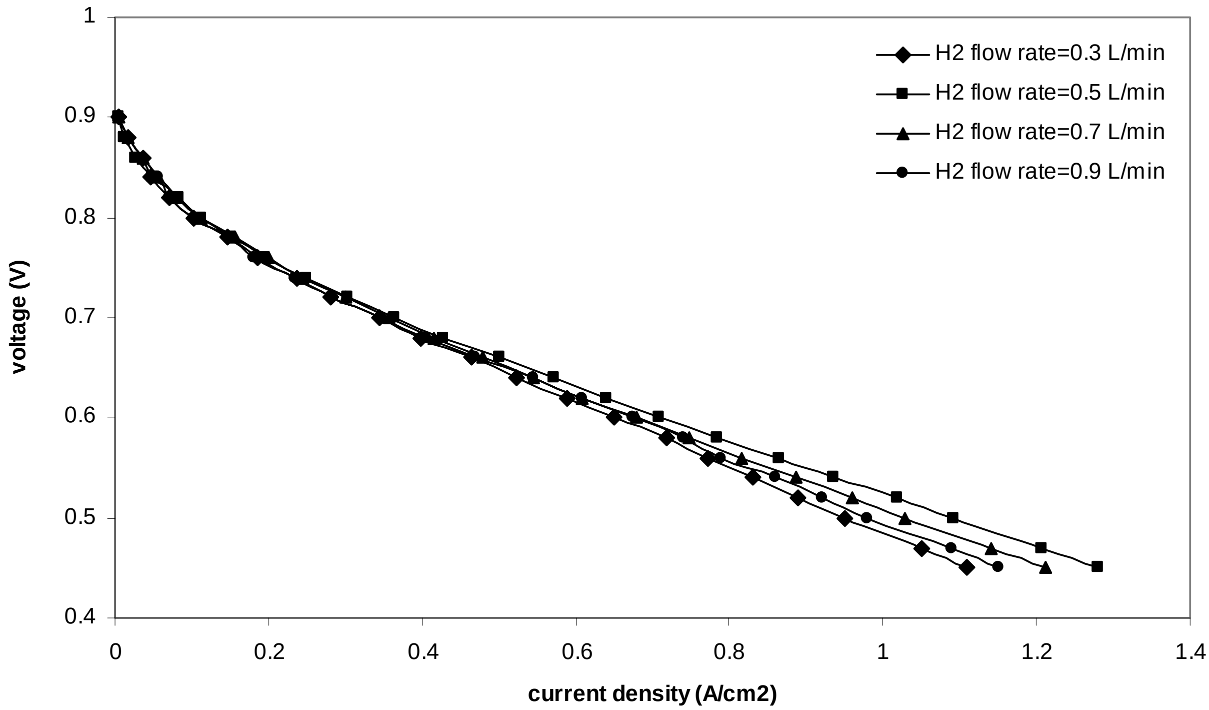

Figure 5. Variation of cell performance at different hydrogen flow rates for $T_{cell} = 60^{\circ}C$, $\dot{m}_{O2} = 0.5L/\min$, P=2.905 bar, $T_{O2} = 55^{\circ}C$ and $T_{H2} = 55^{\circ}C$

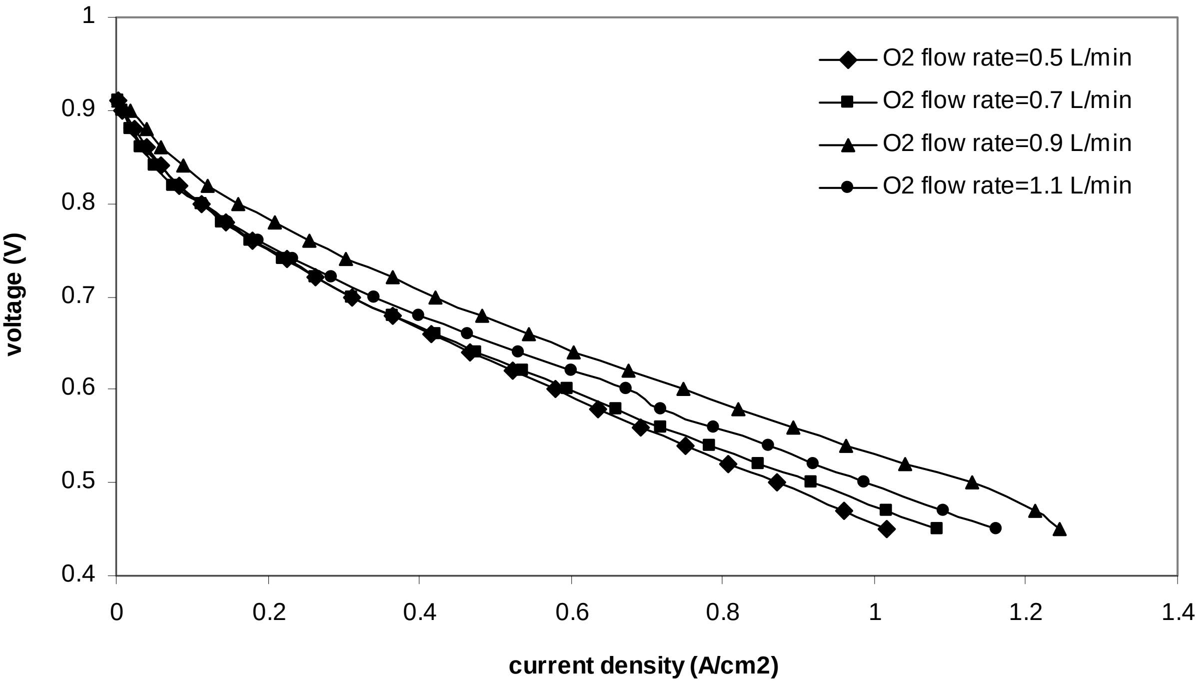

Figure 6. Variation of cell performance at different oxygen flow rates for $T_{cell} = 60^{\circ}C$, $\dot{m}_{H2} = 0.3L/\min$, P=2.905 bar, $T_{O2} = 55^{\circ}C$ and $T_{H2} = 55^{\circ}C$

Figure 7 shows the effect of cell temperature on the performance of the cell at P=2.905 bar, $T_{O2} = 55^{\circ}C$, $T_{H2} = 55^{\circ}C$, $\dot{m}_{O2} = 0.5L/\min$ and $\dot{m}_{H2} = 0.3L/\min$. It is clear that increasing in the cell temperature leads to the increase in the performance of the cell which is due to the decreasing of activation overpotential and increase in the electrochemical reaction. This is because of the exchange current density of the oxygen reduction reaction increases rapidly with temperature due to the enhanced reaction kinetics, which reduces activation losses. A higher temperature leads also to a higher diffusivity of the hydrogen protons in the electrolyte membrane, thereby reducing the membrane resistance and this leads to reducing the potential loss in the membrane. Also Figure 7 indicates that at the conditions of the higher operating voltage (lower over- potential), the influence of the internal flow modification on the overall fuel cell performance is negligibly small. At lower operating voltage conditions, on the other hand, the effect of the internal flow modification on the polarization curves becomes important.

The temperature basically affects all the different transport phenomena inside the fuel cell. The composition of the incoming gas streams depends strongly on the temperature. Assuming the inlet gases are fully humidified, the partial pressure of water vapor entering the cell depends on the temperature only. Thus, the molar fraction of water vapor is a function of the total inlet pressure and temperature, and so the molar fraction of the incoming hydrogen and oxygen depend on the temperature and pressure as well. In Figures 8 and 9 the effect of input hydrogen temperature and input oxygen temperature of the anode and cathode sides at the overall cell performance of the PEM fuel cell for $T_{cell} = 60^{\circ}C$, $\dot{m}_{H2} = 0.3L/\min$, $\dot{m}_{O2} = 0.5L/\min$ and P=2.905 bar are shown. It is clear that at the conditions of the higher operating voltage (lower over- potential), the influence of the oxygen temperature on the overall fuel cell performance is negligibly small but at lower operating voltage conditions the effect of input temperature on the polarization curves becomes important. Also it is clear that by increasing the hydrogen and oxygen temperatures the cell performance enhances that it is due to the decreasing of activation overpotential and increase in the electrochemical reaction at the catalyst surfaces.

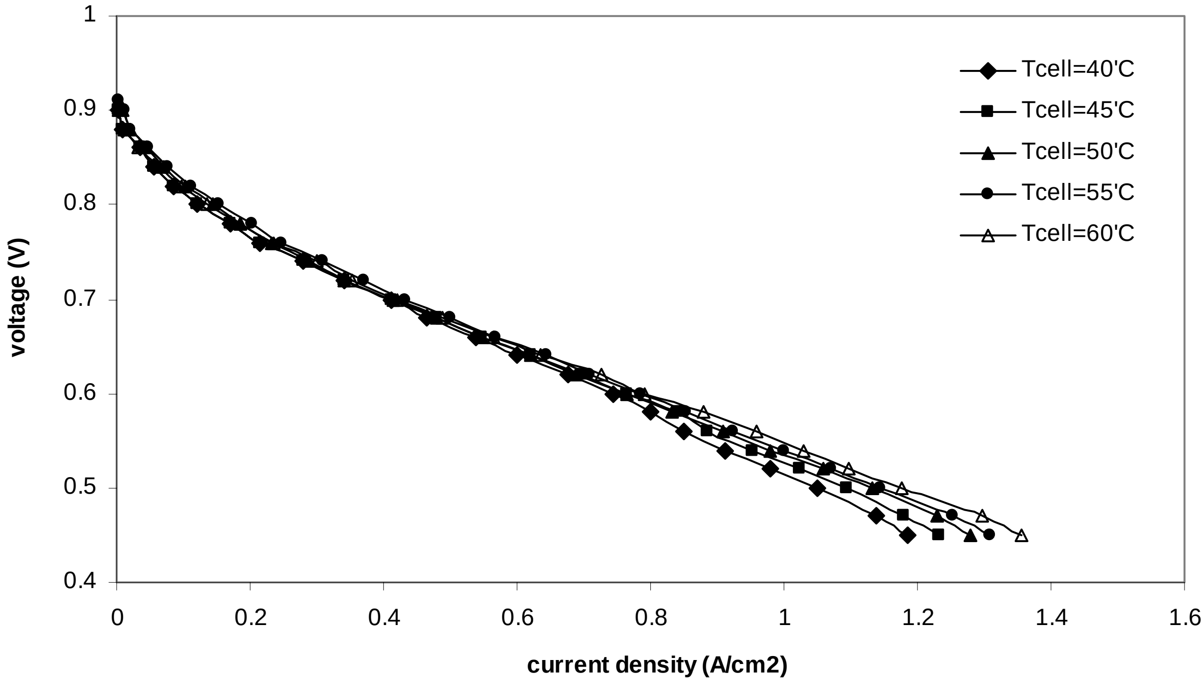

Figure 7. Variation of cell performance at different cell temperatures for P=2.905 bar, $\dot{m}_{H2} = 0.3L/\min$, $\dot{m}_{O2} = 0.5L/\min$, $T_{O2} = 55^\circ C$ and $T_{H2} = 55^\circ C$

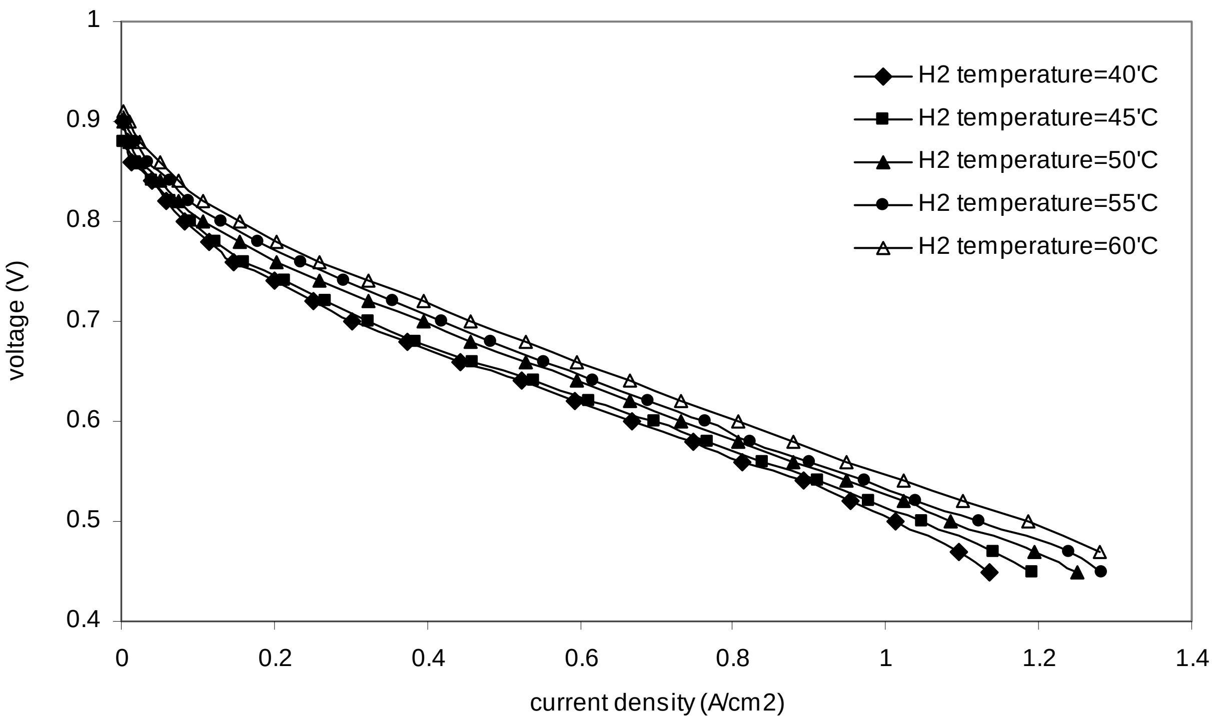

Figure 8. Variation of cell performance at different hydrogen temperatures for P=2.905 bar, $\dot{m}_{H2} = 0.3L/\min$, $\dot{m}_{O2} = 0.5L/\min$, $T_{O2} = 55^\circ C$ and $T_{cell} = 60^\circ C$

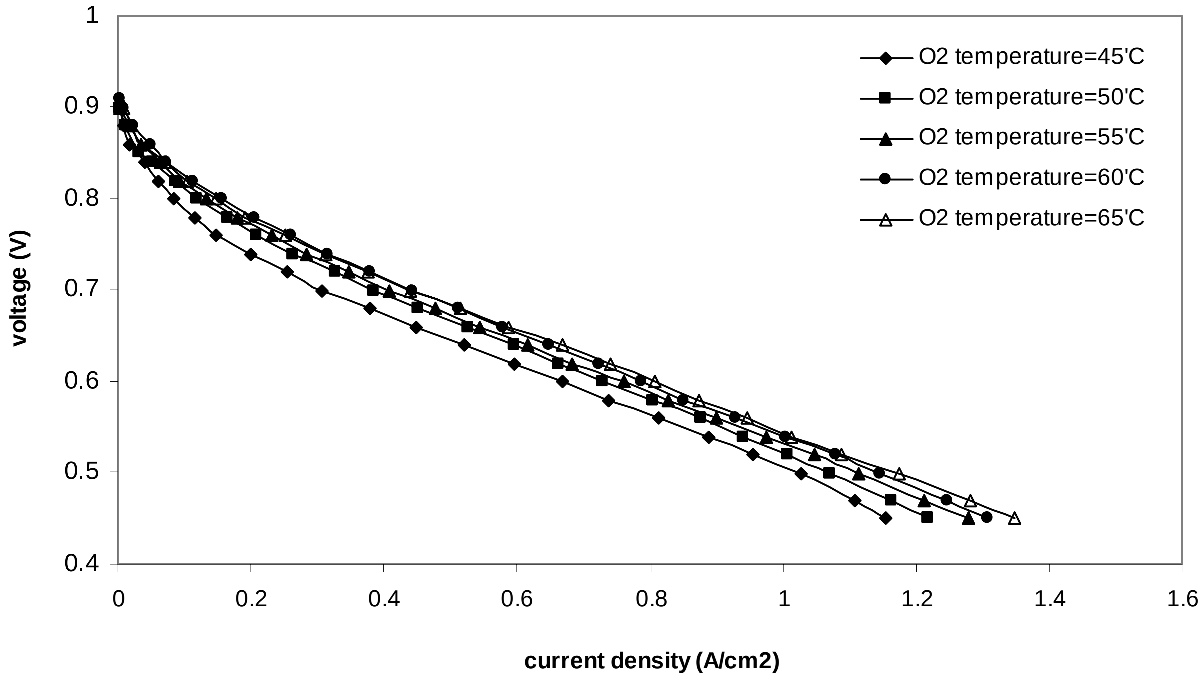

Figure 9. Variation of cell performance at different oxygen temperatures for P=2.905 bar, $\dot{m}_{H2} = 0.3L/\min$, $\dot{m}_{O2} = 0.5L/\min$, $T_{H2} = 55^\circ C$ and $T_{cell} = 60^\circ C$

5. Conclusion

In this study, the effects of input oxygen temperature (T_{O2}), input hydrogen temperature (T_{H2}), cell temperature (T_{cell}), input pressure (P), oxygen flow rate ($\dot{m}_{O2}$) and hydrogen flow rate ($\dot{m}_{H2}$) on the performance of a rectangular channel geometry PEM fuel cell have been investigated experimentally. We have found out that:

● With increasing the input gases pressure, the performance of the fuel cell increases which is due to decrease of ohmic and concentration losses and increase more efficient fuel transport from the GDL to catalyst layer.

● By increasing the hydrogen flow rate and oxygen flow rate the cell performance enhances but when the flow rate increases from 0.7 L/min to 0.9 L/min for hydrogen and from 0.9 L/min to 1.3 L/min the cell performance decreases.

● Increasing in the cell temperature leads to the increase in the performance of the cell which is due to the decreasing of activation overpotential and increase in the electrochemical reaction.

● The effect of oxygen and hydrogen temperature on the performance of the cell is so important that by increasing the hydrogen and oxygen temperatures the cell performance enhances that it is due to the decreasing of activation overpotential and increase in the electrochemical reaction

Nomenclature

I	Current (A)
$\dot{m}_{H2}$	Hydrogen flow rate (L/min)
$\dot{m}_{H2}$	Oxygen flow rate (L/min)
T_{cell}	Cell temperature ($^\circ C$)
T_{H2}	Input hydrogen temperature ($^\circ C$)
T_{O2}	Input oxygen temperature ($^\circ C$)
V	Cell potential (V)

Acknowledgment

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