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ORIGINAL ARTICLE

Parametric study of the proton exchange membrane fuel cell for investigation of enhanced performance used in fuel cell vehicles

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Operating parameters

Abstract This study focuses on the parametric analysis of Proton Exchange Membrane Fuel Cells (PEMFC) to enhance its performance used in Fuel cell vehicles. The study involves fabrication of membrane electrode assembly at 40% Pt/C loading and experimenting with different parameters, viz, cell temperatures, oxygen and hydrogen flow rates and cathode and anode humidification temperatures. The results show that cell temperature has significant effect on the performance of the PEMFC, whereas other parameters produce variation only in the activation polarization region and in the concentration polarization region. A prototype model of FCV, indigenously powered by a fuel cell stack and run continuously without any auxiliary power supply is developed as a viable model for a higher power vehicle. The vehicle's performance is studied by conducting various load tests.

1. Introduction

Fuel cell vehicles (FCVs) have the potential to significantly reduce our dependence on foreign oil and lower harmful emissions that cause climate change. FCVs run on hydrogen gas rather than gasoline and emit no harmful tailpipe emissions. These vehicles are in the early stages of development, and several challenges must be overcome before these vehicles will be competitive with conventional vehicles. However, the potential benefits of this technology are substantial.

A Fuel cell, heart of FCV, is a single step energy conversion device which converts the chemical energy directly into electricity obviating the step of chemical combustion used in a typical process of heat extraction from the fuel [1–10]. It is a direct single step energy conversion device and is therefore associated with high electrical efficiency. Water and heat are the byproducts of the fuel cell along with electricity when pure hydrogen is used as a fuel and therefore it is clean source of energy. The characteristic features of fuel cell are high efficiency, zero/low pollutant emission and fuel flexibility. These three features

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make the fuel cell an extremely desirable option for future power generation.

A Proton Exchange Membrane (PEM) fuel cell consists of three layers, viz, Anode, Cathode and Electrolyte. Hydrogen is made to flow through anode and oxygen traverses through cathode. While hydrogen traverses through anode, it gets reduced to protons and electrons at anode catalyst layer which is made of platinum and supported on carbon back bone. PEM allows only protons to pass through it while electrons would not be allowed as it has affinity towards proton and phobic towards electrons. Electrons are forced to go through the external circuit to reach cathode and there by completes the circuit generating DC electricity. A carbon cloth made Gas Diffusion Layer (GDL), placed over the catalyst layer, is used to diffuse the reactants uniformly over the PEM. Protons reaches onto the other side of PEM through a process named Grottus Mechanism. All the three components, viz, Protons through PEM, Electrons from external circuit and oxygen through cathode GDL meets at cathode catalyst layer. This chemical reaction gives out water and heat.

Hydrogen is humidified to enhance the ionic conductivity of PEM. While protons travel through membrane, it drags water molecules through the membrane. This phenomenon is referred to as electro osmotic drag. Under certain operating conditions, water concentration levels on cathode side are higher than anode side owing to water produced during electro chemical reaction as well as electro osmotic drag. This creates a favourable condition for the water to move from cathode to anode. This phenomenon is referred to as back diffusion.

2. Experimental setup

The Membrane Electrode Assembly (MEA) is fabricated with an active area of 5 cm^2, with a Pt/C (40%) catalyst loading of 1 mg/cm^2 on both the electrodes. Nafion – 117 is used as an electrolyte membrane in this study. The single cell assembly is shown in Fig. 1.

The experiments are conducted using Model 850e Compact Fuel Cell Test Facility as shown in Fig. 2 to obtain the V-I characteristic of the fuel cell.

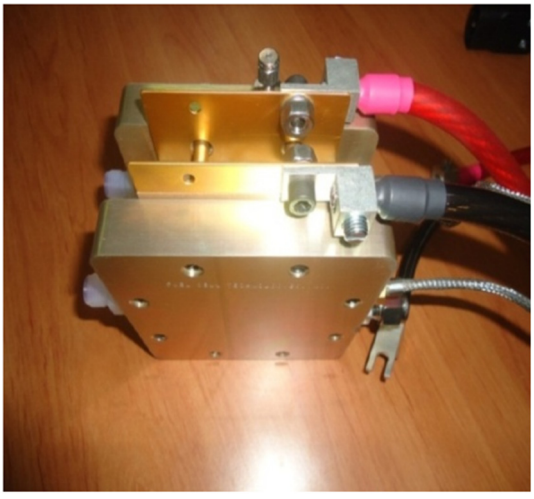

Fig. 1 Assembled Single Cell PEM Fuel cell.

Fig. 2 Fuel Cell Test Station.

3. Experimental results

3.1. Effect of hydrogen flow rate

The experiments are carried out at various hydrogen flow rates ranging from 0.04 to 0.07 liters per minute (lpm) by fixing the oxygen flow rate at 0.05 lpm. The experiments are performed at a cell temperature of 60 °C, anode humidification temperature of 55 °C and cathode humidification temperature of 55 °C. The pressure at both electrodes is maintained at 5 bar.

There is no substantial effect observed in activation and ohmic regions of the fuel cell with increase in hydrogen flow rate owing to the fact that the hydrogen pressure is maintained roughly constant even at different flow rates. When the current density is increased further, a dead point (limiting current density) is reached where the voltage started dropping rapidly as shown in Fig. 3. The limiting current density of the fuel cell is increased proportional to increase in hydrogen flow rate. The limiting current density for 0.07 lpm is 960 mA/cm^2 which is comparably higher than the limiting current density of 915 mA/cm^2 corresponding to 0.04 lpm. Due to high hydrogen flow rate, the concentration of water on the anode side is reduced owing to the reduction in moisture content. Due to

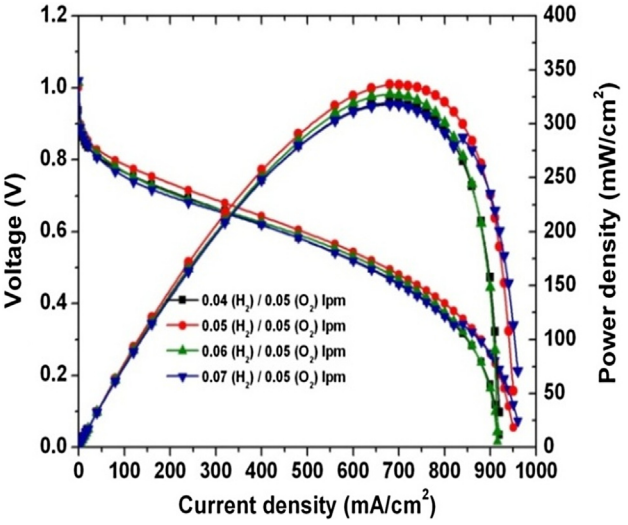

Fig. 3 Effect of hydrogen flow rate.

this concentration gradient or unbalance, the water in the cathode will diffuse to anode and hence high limiting current densities.

3.2. Effect of oxygen flow rate

The experiments are performed at various oxygen flow rates ranging from 0.04 to 0.07 liters per minute (lpm) by fixing the hydrogen flow rate at 0.05 lpm. The experiments are performed at a cell temperature of 60 °C, anode humidification temperature of 55 °C and cathode humidification temperature of 55 °C. The pressure at both electrodes is maintained at 5 bar.

Similar to hydrogen flow rate, there is no substantial effect observed in activation and ohmic regions of the fuel cell with increase in oxygen flow rate owing to the fact that the oxygen pressure is maintained roughly constant even at different flow rates. When the current density is increased further, a dead point is reached where the voltage started dropping rapidly as shown in Fig. 4.

Higher limiting current density was seen at lower oxygen flow rate. However, the limiting current density had been reduced for higher oxygen flow rate. The limiting current density for 0.07 lpm is 920 mA/cm^2, which is much lower than the limiting current density of 1027 mA/cm^2 corresponding to 0.04 lpm. At higher current density, the voltage will rapidly drop to zero because of the difficulty of reactants to reach the electrode. Higher oxygen flow rate will restrain the moisture amount and try to push the water content away from the cathode. The water formed will be removed along with unused excess oxygen in the cathode outlet. Hence, less water formed and water moves from anode to cathode due to electro osmotic drag. Hence low limiting current densities for oxygen flow rates.

3.3. Effect of cell temperature

The experiments are carried out by varying the cell temperature ranging from 30 °C to 80 °C and fixing hydrogen and oxygen flow rates at 0.05 lpm. The anode and cathode humidification temperatures are simultaneously varied at a temperature 5° less than that of cell temperature. The pressure on both sides of electrode is maintained at 5 bar. With increase in cell temperature from 30 °C to 80 °C, the performance of the fuel cell increases as shown in Fig. 5.

The exchange current density and hence the performance increases proportionally with cell temperature, due to the reduction of activation losses. The performance of fuel cell increases proportional to cell temperature and this is attributed not only due to the increase in chemical kinetics of electrode reactions but also due to the increase in mobility of ions through the electrolyte membrane.

The limiting current density of the fuel cell increases in proportional to cell temperature. The experiment is also tried by increasing the cell temperature to 90 °C. This causes complete drying of water content inside the Nafion membrane and the membrane electrode assembly deteriorates, clearly indicating dehydration of the cell which is one of the performance degradation mechanism of a fuel cell associated with water management. Hence reduced performance compared to 80 °C as shown in Fig. 6.

3.4. Effect of anode humidification temperature

The experiments are conducted by varying the anode humidification temperature ranging from 40 °C to 70° by fixing the hydrogen and oxygen flow rates at 0.05 lpm, cell temperature at 60 °C and cathode humidification temperature at 50 °C. The pressure is maintained at 5 bar.

The ohmic region of the polarization curve for various anode humidification temperatures are practically parallel to each other as shown in Fig. 7. This demonstrates that the electrical resistance of the fuel cell bringing about ohmic losses does not differ altogether. As the pressure is maintained constant, ambient temperature is the only parameter which affects the molar fraction of water vapor. Hence at lower temperature and for the same relative humidity, the molar fraction of water vapor present is low. At low current densities there is a defi-

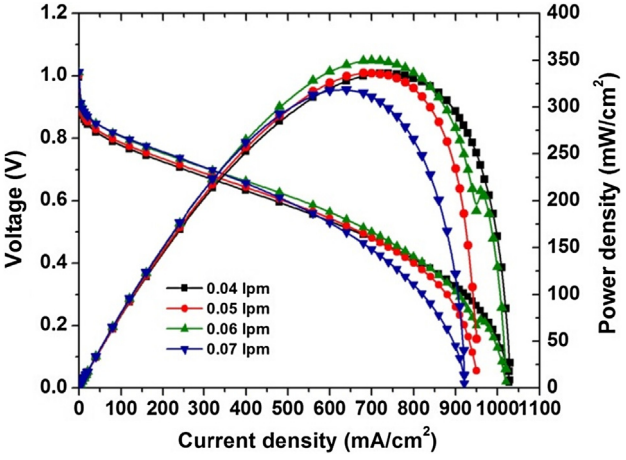

Fig. 4 Effect of oxygen flow rate.

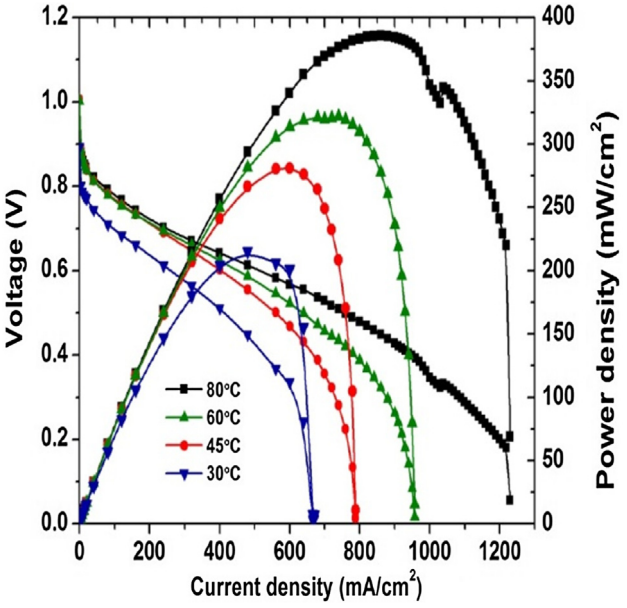

Fig. 5 Effect of cell temperature.

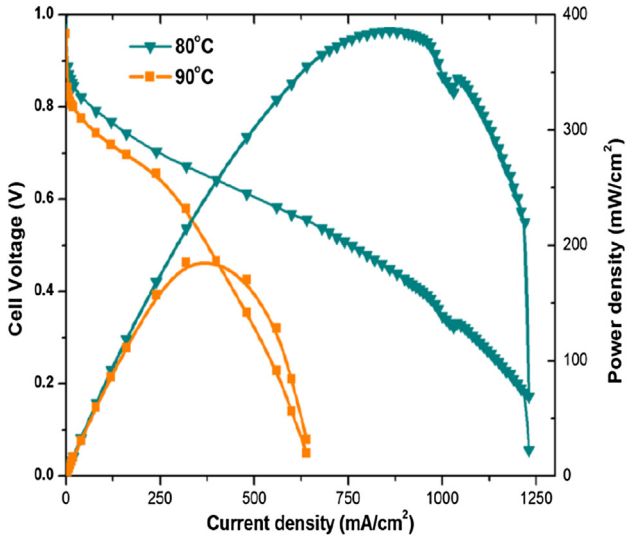

Fig. 6 Performance at 80° and 90 °C.

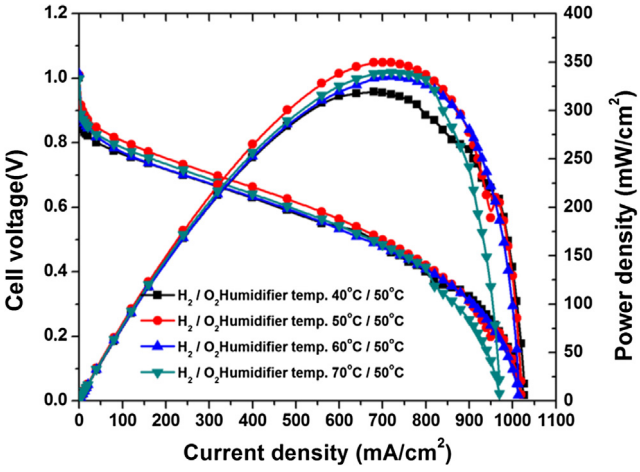

Fig. 7 Effect of anode humidification temperature.

ciency of water in the catalyst layers due to which there is a reduction in active surface area of the catalyst. This results in the decreased cell voltage of the fuel cell. Under these circumstances, movement of water from cathode to anode is predominant through back diffusion than the water transfer from anode to anode through electro-osmotic drag. This results in the dehydration of the catalyst layer at cathode side of the fuel cell. At higher current densities, since the water production rate is high, the cell voltages are practically constant at various anode humidification temperatures and thus the cathode catalyst layer is better hydrated. This phenomenon when supplemented with high water vapor content at the anode side leads to decrease in limiting current density. Thus limiting current density decreases with increase in anode humidification temperature as depicted in Fig. 7.

3.5. Effect of cathode humidification temperature

The experiments are conducted by varying the cathode humidification temperature ranging from 40 °C to 70° by fixing the

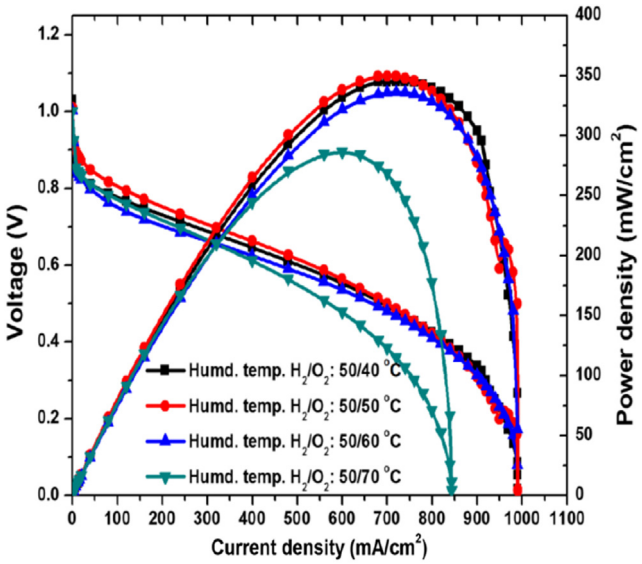

Fig. 8 Effect of cathode humidification temperature.

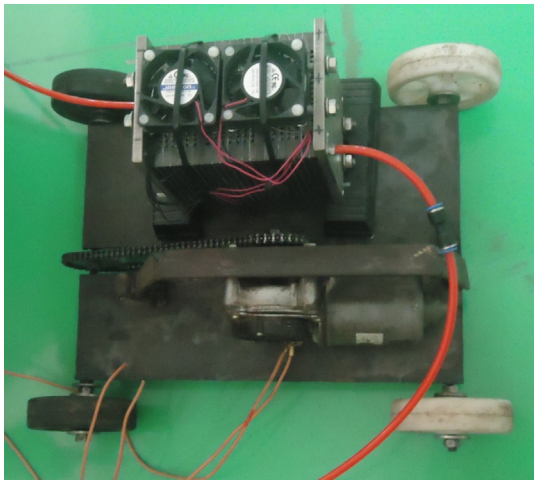

Fig. 9 Model vehicle powered by Fuel cell.

hydrogen and oxygen flow rates at 0.05 lpm, cell temperature at 60 °C and anode humidification temperature at 50 °C. The pressure is maintained at 5 bar.

The molar fraction of a water vapor is the function of temperature since the pressure and the humidification is kept constant. When the humidification temperature is less than the cell temperature, the water vapor content is less. The result is the increase in molar oxygen mass fraction content at the catalyst layer. Hence, better cell reaction at lower humidification temperature which can be seen in the increased performance at lower current density.

The limiting current density decreases with increase in cathode humidification temperature as depicted in Fig. 8. This deceasing trend is attributed not only to the reduction in concentration of reactant gases but also to the reduction in effective porosity of the GDLs placed on both ends of electrolyte membrane.

Table 1 No load test results.

S.N	Off		Starting		Midway	
	Current	Voltage	Current	Voltage	Current	Voltage
1	0	12.50	1.20	11.40	0.710	11.50
2	0	12.56	1.60	11.40	0.740	11.57
3	0	12.47	1.45	11.40	0.752	11.50
4	0	12.50	1.40	11.40	0.732	11.50

Table 2 Fuel cell stack laden test results.

S.N	Off		Starting		Midway	
	Current	Voltage	Current	Voltage	Current	Voltage
1	0	12.56	2.08	11.36	0.765	11.60
2	0	12.60	1.30	11.30	0.836	11.70
3	0	12.60	1.66	11.10	0.829	11.60
4	0	12.60	1.37	11.40	0.826	11.60

4. Prototype vehicle powered by Fuel Cell

The prototype vehicle powered by Fuel Cell is shown in the Fig. 9. Based on the performance study made on the fuel cell stack, the vehicle prototype development was carried out. The prototype was to be made as a viable model for a higher power vehicle which can be completely based on this model. The available voltage and power from the fuel cell stack was a major limiting factor in the development of the prototype. The platform, drive and controls were to be designed keeping in mind the feasibility of incorporating them on a full capability vehicle. This prototype is to be seen as a scale down version of an advanced vehicle with all its features such as speed controller, directional switches, safety setups, drive adjusters, etc. the performance study of the fuel cell stack was conducted prior to the development to make sure that the compatibility of the vehicle to the fuel cell stack is to its fullest and there is an established correlation between the two functions so as to facilitate further developments in either of them.

5. Performance study of FCV

5.1. No load test

The fuel cell driven prototype vehicle was first put into a no load test, the voltage and current are monitored which is drawn during the start of the vehicle, when it is running midway and during the off position. The results are tabulated in Table 1.

5.2. Fuel cell stack laden test

The fuel cell stack is placed on the platform of the vehicle and tested. During this run, the weight of the stack was carried by the vehicle, and now the various parameters were noted and tabulated in Table 2.

5.3. Fully laden test

The vehicle was then fully laden (fuel cell stack + other loads) to its capacity and now the same tests were carried out. The current and voltage drawn were noted at regular intervals with hand held meters. These values are tabulated in Table 3.

Table 3 Fully laden test results.

S.N	Off		Starting		Midway	
	Current	Voltage	Current	Voltage	Current	Voltage
1	0	12.50	2.50	11.20	0.954	11.40
2	0	12.50	2.20	11.00	0.903	11.30
3	0	12.50	1.70	11.00	0.929	11.20
4	0	12.40	2.23	11.10	0.896	11.30

The vehicle was given a no load condition and an open circuit voltage test was carried out by setting the inlet pressure at 5 kg/cm^2 and reactant gases flow rate at 2 lpm. The results of the experiments are plotted in the Figs. 10–13. The stack voltage is seen to show a negligible variation between 11.9 V and 12.35 V. The same trend is noted in the current drawn with the values ranging from 0.63 A to 0.77 A. The downward trend in both the parameters can be attributed to the increase in the cell temperature from 41 °C to 55 °C.

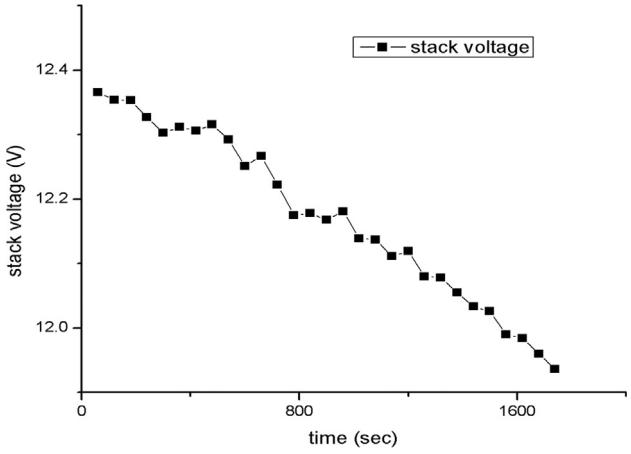

Fig. 10 Stack Voltage (V) vs Time (sec).

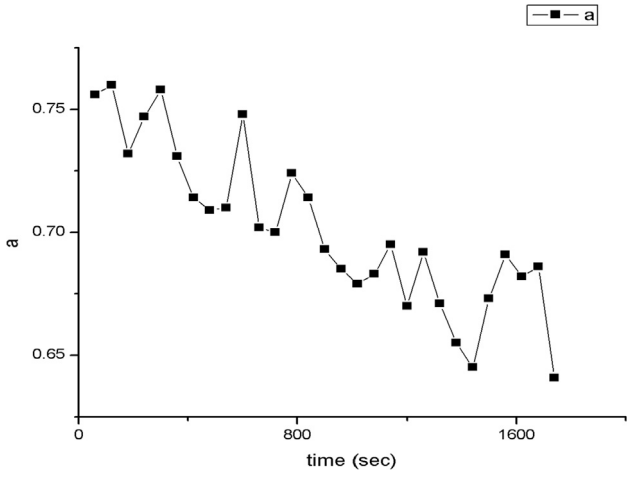

Fig. 11 Current (A) vs Time (sec).

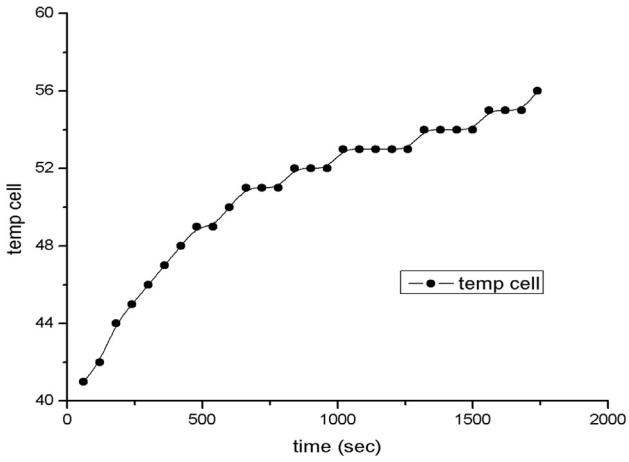

Fig. 12 Cell Temperature vs Time (sec).

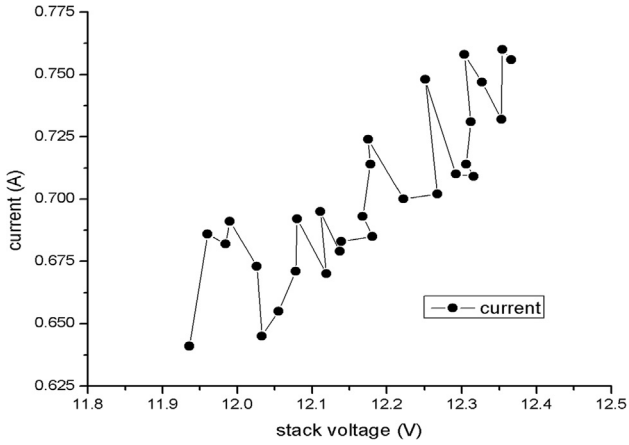

Fig. 13 Current (A) vs Stack Voltage (V).

6. Conclusion

In this Study, membrane electrode assembly was fabricated with 40% Pt/C loading on the gas diffusion layer. The effect of operating parameters was studied by varying the levels of the required parameter when other parameter values are kept constant. The results show that cell temperature has significant effect on the performance of the PEMFC, whereas other parameters produce variation only in the activation polarization region and in the concentration polarization region. A four wheeled prototype model of FCV, indigenously powered by a fuel cell stack and run continuously without any auxiliary power supply is developed as a viable model for a higher power vehicle. The vehicle's performance is studied by conducting various load tests.

Acknowledgement

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