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Assessment of Various Parameters of Low Temperature PEM Fuel Cell Components

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Abstract

Bipolar plate for Proton Exchange Membrane (PEM) fuel cell was fabricated with various materials and characterized by different techniques. Two types of gas flow fields, serpentine & parallel, were designed for bipolar plates and their effect on the functioning of fuel cells was investigated. Pressure drop between the two designs, at inlet and outlet of gases was different and its effect was reported. In the fabrication process of membrane electrode assemblies (MEA), the platinum catalyst was synthesized in the laboratory and this catalyst was deposited on the Nafion membrane with the help of ionomer emulsion. Then gas diffusion layers were placed on both sides of the membrane. Different MEAs versions (imported and indigenous) were assembled and tested in the fuel cells and their efficiency was evaluated in terms of current, voltage and power. A fuel cell test stand was developed to operate and test the working of single cell and fuel cell stack is also described. Polarization curves were drawn to evaluate the performance of fuel cells. These studies are directed at the development of different fuel cell components which are tested under the same conditions for comparison.

Key words: PEM fuel cell; Bipolar plates; MEA, Catalysts; Nafion^T, Proton exchange membrane, Endurance tests.

1. Introduction

Fuel cells are undoubtedly one of the key alternatives to replace conventional energy means, as a clean electrical energy source for both transportation and stationary applications. Since 1960, when NASA for the first time used fuel cell in space shuttle as a backup of electric supply, the research work got under way on all types of fuel cells. However over the past few years Proton Exchange Membrane Fuel Cell (PEMFC) has emerged as a leading fuel cell in portable and especially in automobile applications due to its operation at low temperature, comparatively simple construction, high power density and ease of operation [1, 2]. Several companies are presently offering PEMFC for commercial uses including portable, stationary and automobiles [3, 4].

The PEM fuel cell consists of bipolar plates, which also referred to as flow field plates and play important role in fuel cell i.e. conducting current, keeping the gases separate and managing water electrode assembly (MEA), which is where the fuel cell's core technology resides. The MEA is comprised of a polymer electrolyte material for transporting hydrogen ions from the anode to cathode, with a platinum catalyst layer and gas diffusion layer (GDL) on either side [18].

The process of PEM fuel cell is very simple. Hydrogen is supplied to the anode and the resulting reaction is as follows:-

$$2H_2 + \text{Catalyst} \rightarrow 4H^+ + 4\,e^-$$

Oxygen is supplied to the cathode and the reaction is;

$$O_2 + 4H^+ + 4e^- + \text{Catalyst} \rightarrow 2H_2O$$

The over all reaction gives:

$$2H_2 + O_2 + \text{Catalyst} \rightarrow 2H_2O + \text{Heat} + \text{Electricity}$$

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Usually 7 W electrical power may be produced with the 25 cm^2 effective area of MEA in a single cell. Stichometrically, the amount of oxygen consumption in such a fuel cell is 2.98×10^{-3} Kg/hour, while the hydrogen consumption is 0.378 x 10^{-3}Kg/hour, which is very low. During the operation of fuel cell water is produced at the rate of one mole for every 2 electrons and in a single fuel cell the water production is usually 3.36×10^{-3} Kg/hour which is disposed of in vapor form when the oxygen/air discharged from the cathode of the cell. Heat is also produced when a fuel cell operates which is usually 5.5 W. This Heat energy is leaving the fuel cell in three forms; Electricity, sensible heat and latent heat of water vapor. Therefore, for the management of 5.5 W heat energy there is no need of any heat management system [19].

In present investigation, single fuel cell and fuel cell stacks were designed, fabricated, assembled, operated and tested for various parameters such as current flow, voltage, power and current density. MEAs were prepared by different procedures with different active areas and tested for use in PEM fuel cells. Bipolar plates of different materials were also fabricated and tested for their application in single fuel cell and fuel cell stacks. Results are reported and discussed.

2. Experimentation

2.1 *Fabrication of fuel cell test system*

Figure 1 shows the portable fuel cell test system, which was built in a laboratory with the available resources. This system was consisted of two gas cylinders (Oxygen & hydrogen), two separate bubble type humidifiers along with liquid receivers for oxygen & hydrogen humidification and stainless steel tubes wrapped with silicon wire heaters to maintain the temperature of gases. To measure the different parameters of the fuel cell e.g. pressure, temperature, potential and current, respective digital Multimeter (UNI-T UT53) and analog meters were installed. To apply the resistive load on the fuel cell a Rheostat (0-16.2 Ω and 5A, Fisher Scientific Co, USA) was available.

Moreover, an array of LEDs of 3 W electric power was also installed on the platform for visual identification and monitoring the power characteristics against different fuel cell parameters.

2.2 *Components of Fuel Cell*

Bipolar and monopoler plates of different materials including graphite, aluminum, copper, gold plated copper, stainless steel and carbon polymer composite materials (Graphite+ABS, Graphite+ Polypropylene with different proportions) were designed and fabricated.

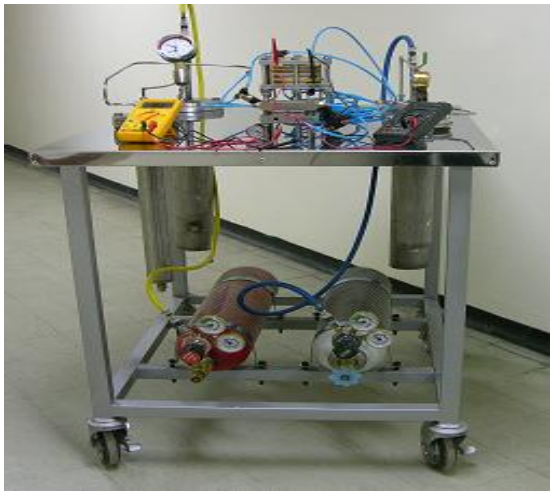

Figure 1: Fuel cell test system.

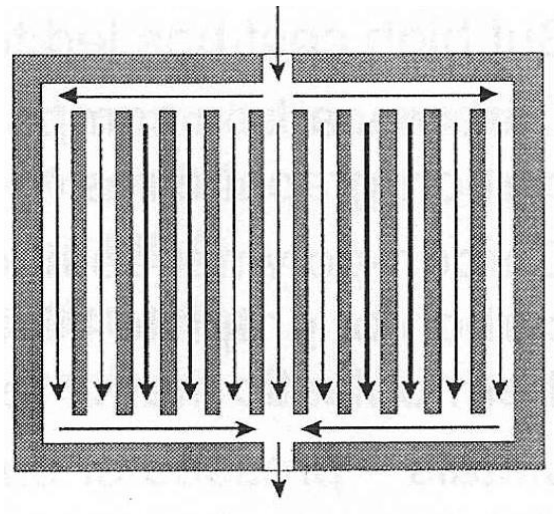

Figure 2(a): Configuration of parallel flow pattern.

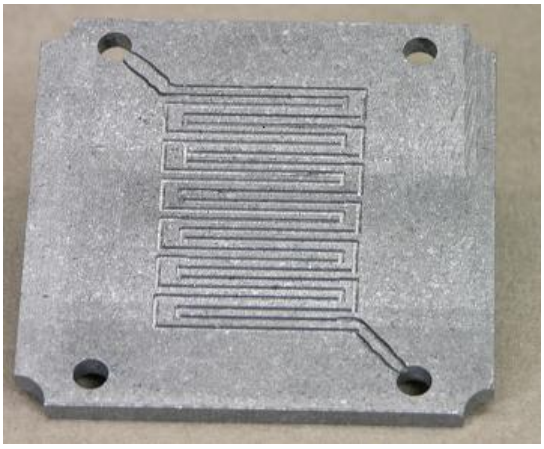

Figure 2(b): Serpentine flow pattern on a 16 cm^2 effective area monopolar plate

Two types of flow patterns as shown in Figure 2(a) and 2(b) were employed, parallel flow pattern [Fig. 2(a)] and double serpentine [Fig. 2(b)]. In some cases double serpentine flow pattern was used for the hydrogen flow and parallel flow pattern was used for the oxygen flow. The width of channels was 1 mm and space between the channels was also 1mm. The depth of the channels was 1mm.

In the fabrication process of membrane electrode assemblies (MEA), the platinum catalyst was synthesized in the laboratory by converting platinum metal into platinum powder by electro-deposition method and then sintered in controlled conditions in a vacuum furnace [20]. The synthesized catalyst was deposited on the Nafion membrane with the help of ionomer emulsion. Then gas diffusion layers were placed on both sides of the membrane (25 micron thickness Toray Carbon paper). The MEA so fabricated was pressed in a hot press at 225^0C to achieve the glass transition state and to integrate all of the 5 layers with each other [21].

2.3 *Measurement of Different Parameters*

Four-probe method was employed to observe the potential drop in different components and fuel cell. The constant current was allowed to pass through the sample by digital multi-meter Kyoritsu Model 1009. The potential drop was measured across the probes with a 195A digital multi-meter at ambient conditions where probe distance signifies the sample length. The potential drop observed was the average value obtained for both directions of current flow. Conductivity was calculated by the application of following equation [22], $\delta = DI/VA$, Where, "D" is the distance between voltage contacts, 'I' is current passing through current contacts, 'A' is the cross-sectional area of the specimen and 'V' is the voltage developed across voltage contacts.

Galvanostatic measurements were made by using the apparatus Bechman Electrocscan^{TM-30} in a 3 electrode cell containing 50 ml of solution (1 M H_2SO_4 + 1M CH_3OH + pure deionizd water) in order to characterize platinum as catalyst material. The cell temperature was maintained at 30^0C. Before and during the Galvanostatic measurements oxygen was removed from the solution by passing nitrogen through the solution for 15 minutes and then keeping the nitrogen flowing over the surface of the solution throughout the experimentation to keep the solution free of oxygen. Platinum disc electrode whose surface area was 0.196 cm^2 was polarized galvanostatically from 1 mA to 100 mA and corresponding potential values were measured and recorded using digital voltmeter.

The effect of temperature on reaction rate during the operation of fuel cell was studied quantitatively. The current produced by the fuel cell, which is the rate of reaction, measured by connecting an ammeter directly to it. The current produced was dependent on the resistance of the meter used and it was 17.3 Ohms. This experiment was performed at 10, 28, 40 and 50^0C. The cell was cooled by putting it in chilled water beaker and heated by placing it in hot water. The corresponding measurements of current produced against the respective temperature and voltage were recorded and respective graphs were made [23].

2.4 *Fabrication of fuel cell stack*

Two PEM fuel cell stacks were fabricated, one comprising 3 cells of MEA effective area 25 cm^2 and other, as shown in Figure 3, by assembling 5 cells with MEAs having an effective area of 50 cm^2 sandwiching between two bipolar plates, two monopolar plates made up of gold-platted copper and the rest of the two bipolar plates were Nickel-plated copper.

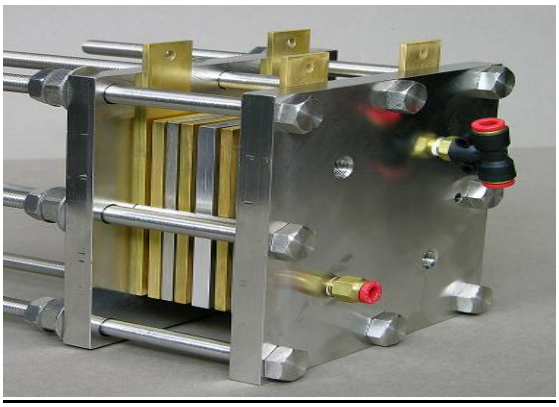

Figure 3: PEM fuel cell stack with gold plated and nickel plated bipolar plates.

The stacks were operated for different time spans, current, voltage, power out puts and endurance tests.

3. Results and discussion

3.1 Effect of Bipolar Plate material on fuel Cell Performance

A number of available materials were used to fabricate the bipolar plates including graphite, aluminum, copper, stainless steel and graphite composite material.

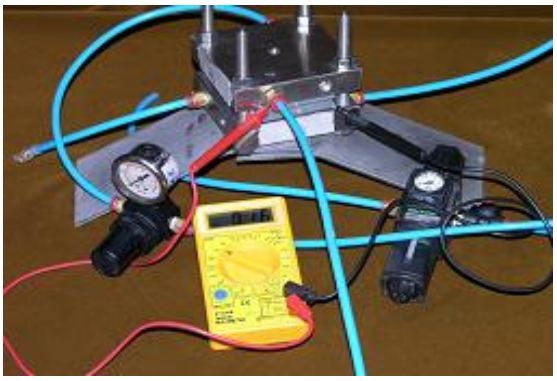

Figure 4: The demonstration of a single PEM fuel cell in operation.

The single PEM fuel cell (having aluminum bipolar plates) and demonstration of its operation along with measuring devices is shown in Figure 4.

Following parameters of the fuel cell were noted during its operation.

Oxygen Pressure: 1 bar
Hydrogen pressure: 0.4 bar
Temperature: 20^{o}C
Duration of operation: 2 Hours

Figure 5 presents performance of the single cells assembled with stainless steel, graphite composite, aluminum and gold plated copper bipolar plates. The results of Figure 5 revealed that the open circuit voltage (OCV) of the single cells was almost the same at 0.8V. As we can see from the curves that with the increase of current drawn from the fuel cell, the potential suddenly drops in each case. The graph presented shows that with the increase of electrical resistivity the performance of cell decreases.

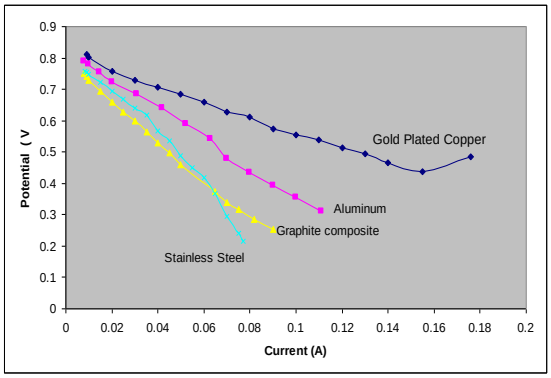

Figure 5: Effect of bipolar plate materials on the performance of PEM fuel cells demonstrated by the respective characteristic curves.

The curve for the bipolar plate made with gold plated copper has minimum electrical resistance, hence it resides on the top and has the best polar curve, while aluminum has intermediate and graphite composite and stainless steel are inferior ones having the high electrical resistance as compared to the gold and aluminum.

The electrical resistance values measured by digital multimeter (UNI-T UT53) for various bipolar plate materials are given Table 1. These results revealed that the resistance of graphite composite material is higher then that of metals. It has been concluded by [11-12, 17, 23] that with the increase of electrical resistivity the performance of cell decreases.

Tabl 1: Resistance of different bipolar plate materials.

S. No	*Name of material*	*Resistance* (Ohms)
1.	Composite material developed in the Fuel Cell Laboratory	0.3

2.	Composite material developed by L.N Green Power China	0.3
3.	Composite material developed by Gas Hub Singapore	0.2
4.	Composite material developed by Shunk Germany	0.2
5.	Impregnated graphite in the laboratory	0.2
6.	Stainless steel (304 L)	0.1
7.	Copper (99% Pure)	0.0
8.	Gold plated copper	0.0
9.	Aluminum	0.0

The electrical conductivity is the inverse of electrical resistivity. Hence, it was measured with four-probe method for the graphite composite bipolar plate material and was found as 95 S/cm. Electrical conductivity is strongly dependent on temperature. In metals, electrical conductivity decreases with increasing temperature. Over a limited temperature range, the electrical conductivity can be approximated as being directly proportional to temperature. In order to compare electrical conductivity measurements at different temperatures, they need to be standardized to a common temperature.

3.2 Effect of pressure drop on the performance of fuel cell.

The effect of pressure drop through serpentine and parallel flow patterns were investigated by carrying out experiments and making measurements of pressure drop, current and voltage produced and power stability on such conditions. The results of pressure drop through serpentine and parallel flow patterns along with effect on current and voltage are summarized in the Table 2.

Table 2: Effect of pressure drop through serpentine and parallel flow patterns

Flow Pattern	C_p (Psi)	H_p (Psi)	P_i (Psi)	P_O (Psi)	E (V)	I (mA)
	Hydrogen				For Cell	
Serpentine	22	20	20	14	0.8	125
Parallel	22	20	20	17	0.7	103
	Oxygen					
Serpentine	50	48	48	42	-	
Parallel	50	48	48	45	-	

Cp: Cylinder pressure, Hp: Humidifier pressure, Pi: Inlet pressure, Po: Outlet pressure

A high pressure drop was noticed in case of serpentine flow fields and a low pressure drop was recorded in parallel flow patterns of the two gasses In both flow patterns different current & voltage characteristics were also noticed as given in Table 2.

It has been also observed that the cross sectional area of flow channels is important in regard to pressure drop. So different cross sectional areas were adopted and pressure of gas trough these areas were investigated. It was observed pressure drop by decreasing the cross sectional area of the flow channel and it was ideal against the $1mm^2$ area..

As air is supplied to the fuel cell at the expense of electrical efficiency of the fuel cell system and pressure drop of supplied air is directly proportional to the electric power consumed by the compressor or blower, so pressure drop of supplied air is least required and efforts are made to keep it at minimum level. On the contrary pressure drop is the driving force required for the transportation of water from the flow channels of PEM fuel cell cathodes, so a minimum pressure drop required for the transportation of water droplets through channels of cathodes is always desired.

Actually bipolar plates offer multidimensional important factors, e.g., architecture for cell stacking, access of fuel and oxidant to the MEA, conduction path for the current, heat transfer, and disposal of unused gases and products of the reaction. Therefore, following properties are very important for the bipolar plate material: good electrical conductivity, good thermal conductivity, good mechanical properties, e.g., compressive strength, tensile strength, machine ability, thermal and mechanical stability within the fuel cell operation conditions. Ideally, the material should be nonporous and impermeable for oxygen, hydrogen and water and it should not be corrosive in nature in fuel cell prevailing conditions. In the present study composite graphite bipolar plate was found to be best in respect of cell performance, machine ability, low specific weight and cost etc.

3.3 Effect of catalyst materials on the performance of fuel cells

The most important aspects of the PEM fuel cell were the processes regarding preparation of catalyst materials. Efforts were made to explore the availability and preparation of catalyst materials and their testing. PEM fuel cells were fabricated by using different specifications of MEA are presented in the Table 3.

Table 3: Fuel cell operation parameters for the MEAs made by different catalysts & conditions

Single cell Description	Wire mesh Electrodes	MEA by E-Teck	Indigen-ous MEA	MEA by Shunk
Temp. ^{0}C	15	26	20	23
MEA (cm^2)	16	25	50	100
H_2 Flow L/h	40	150	120	150
0_2 Flow L/h	80	400	250	300
Open Voltage	0.8	0.92	0.93	0.95
Cell Temp. ^{0}C	27	30	36	45

The stichometric requirements of hydrogen and oxygen for a PEM fuel cell have been calculated but in practical applications an extra amount is supplied due to following reasons; All of the molecules of the hydrogen can not be oxidized and the reaction products are required to be driven out from the anode as well as cathode side which can be achieved by the circulation of an extra volume of gases. To optimize this extra volume of gases, the %age utilization factor of gases is required to be investigated.

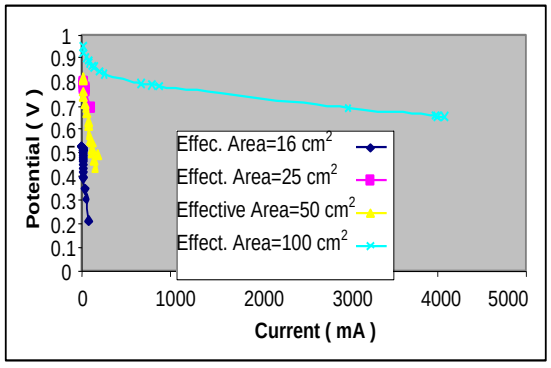

Figure 6: Characteristic Polarization curves for 4 single cells of different MEA Configurations.

The polarization curves for all of the single cells presented in the Table 3 have been drawn on a single graph for comparison in Figure 6. All of the cells have different geometries, MEA configuration, catalyst, gas flow field patterns, fabrication history and different assembling parameters. Hence, they exhibit different polarization curves, presenting the accumulated effect on the performance characteristics.

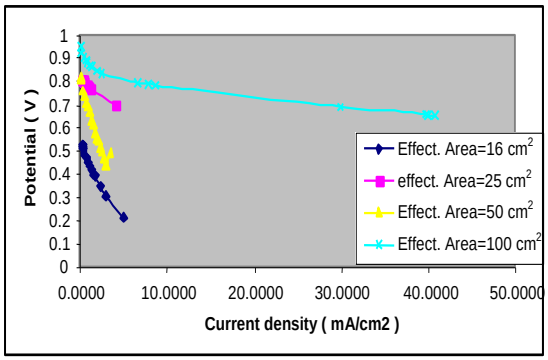

Figure 7: Performance comparison by a plot of Current density Vs potential of the single cells.

Figure 7 is a true representation of performance indicator of all of the above mentioned fuel cells. These results indicated that by increasing the current density the voltage of the cell decreases. Hence to draw the required current density an optimum voltage can be predicted or adjusted accordingly for the specific cells.

The power produced in a fuel cell is directly proportional to the current drawn from the cell as indicated in Figure 8. Hence a compromise can be made and an optimum power can be drawn from a fuel cell.

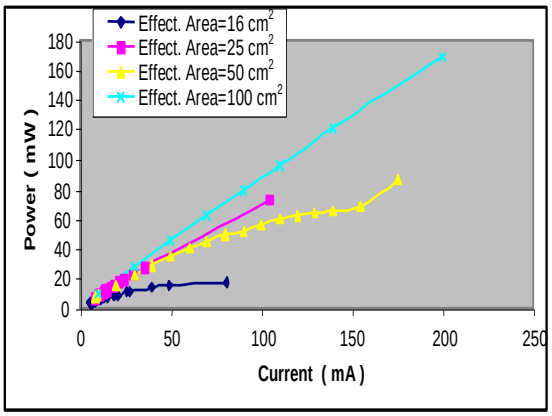

Figure 8: Relationship of power produced with the current .

By increasing the potential, as shown in Figure 9, the power produced or drawn decreases and it can be adjusted or optimized accordingly. This effect is

minimum in case of a fuel cell with mea area 100 cm^2.

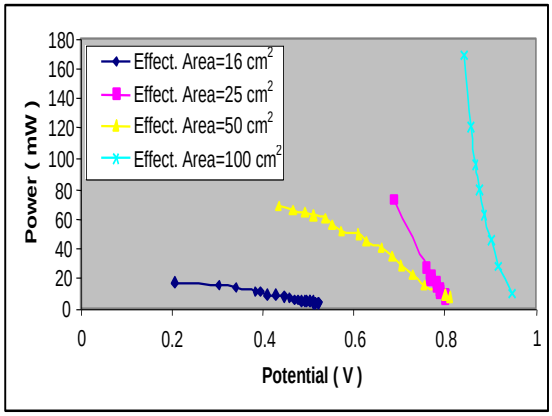

Figure 9: Representation of inverse relationship of potential with the power produced.

3.4 *Effect of Temperature on Electrochemical reaction rate.*

The experiment was performed from 10°C to 50°C. The current produced at 10°C was 5.2 A and it increased to 13.7 A when temperature raised to 50°C. This increased in current by temperature is an indication of the respective increase in the rate of electrochemical reaction in the fuel cell. Figure 10 shows the change in electrochemical reaction i.e. current with rise in temperature.

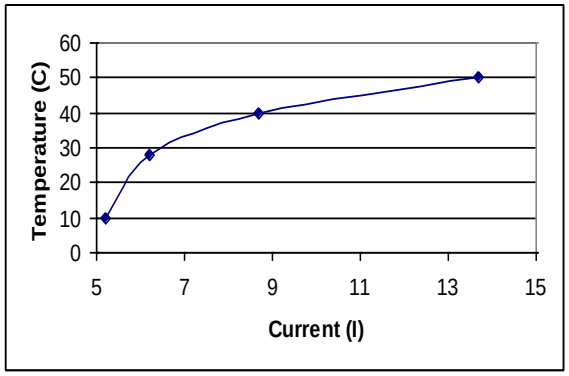

Figure10: Graph depicting the change in electrochemical reaction rate with the change in temperature.

Moreover, the same behavior was studied during the fuel cell operation that in the start the electrical power is at low levels and with the passage of time it increases. This is due to the reason that in the beginning the cell was at ambient temperature (20°C) and both hydrogen & oxygen were being supplied at this temperature. The electrochemical reaction is an exothermic in nature so the temperature rises within the fuel cell. As the ideal temperature for this reaction is 70-80°C, the potential rises to highest level as it approaches but again there is a limit about this temperature (80°C), above which the Nafion membrane may get short circuiting.

3.5 Galvanostatic measurements.

The study of Galvanostatic polarization of platinum disc electrode in the presence of H_2SO_4 /NaOH + CH_3OH for the determination of catalytic activities of the catalysts by drawing the Tafel plot of over potential vs current densities and calculating the slope of the curve obtained and using this slope in the Tafel equation to calculate I_o(J_o) which is an indicator of the catalytic activity [24].

The over potential was plotted against the log of current density and the resulting slope of the curve Tafel slope was calculated which was 0.591.

And we know from Tafel equation;

Over potential = **S** = (2.3 RT/ anF) X log I_o - (2.3RT/ anF) log I

= (2.3 RT/ anF)(log I_o - log I)

Where over potential = Potential when current flows Equilibrium potential

= 1.33 ـ 1.2

= 0.13

While the calculated Slope = 0.591

= 2.3RT/ anF

= 0.00831

= 8.31 X 10^{-3}

By putting the respective values in Tafel equation

0.13 = 0.591(log I_o ـ log I)

0.13/0.591 = log

log I_o = (0.13/0.591) + log I

log I_o = 0.2199 2.3

I_o = $\log^{-1}$(2.08)

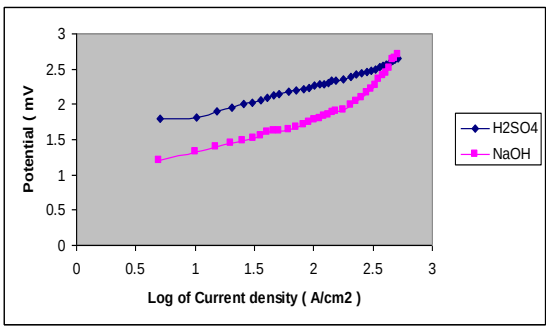

Figure 11: Comparison of Tafel plots of oxidation current densities for the surface area of platinum towards the methanol Galvanostatic polarization in H_2SO_4 and NaOH

While the value of I_o is a representation of catalytic activity and the value of I_0 = 8.31 x 10^{-3} is comparable to the value of I_o for platinum in H_2SO_4 given in Table 1 [19].

The catalytic activities of the smooth platinum electrode towards methanol electro oxidation in 1 M H_2SO_4 also exhibited similar behavior as that in 1 M NaOH but the curves presented in Tafel plots gives us the difference in slope values highlighting the difference in over potential exhibiting the catalytic behavior in acidic and basic media as shown in Figure 11.

3.6 Performance of fuel cell stack

The fuel cell stacks fabricated indigenously were tested for current, voltage, power and endurance tests. Following are the results:

A 3 cell stack delivered 18 W at a potential of 2.5 V and it was used to illuminate an LED display board.

A 5 cell stack delivered 22 W at a potential of 4 V. Both of these stacks were operated for several hours for endurance tests.

The characteristic polarization curves were drawn for the indigenous fuel cell stacks for comparison with the fuel cell stacks fabricated by the world's famous fuel cell manufacturers, e.g., Gas Hub (Singapore), Palcan Fuel Cells (Canada), Ballad (Canada). The trend of the indigenous fuel cell stack is almost same as that of the other fuel cell stacks as shown in Figure 12.

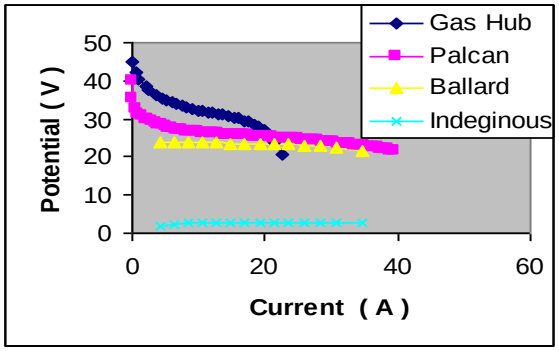

Figure 12: A comparison of polarization curves for various fuel cell stacks representing inherent behavior.

The Figure 13 shows the individual contribution of the single cells in the over all out put of the fuel cell stack in the form of current and voltage. The variation of current and voltage is very much clear and it is due to a lot of factors e.g., gas pressure, temperature, contact resistance etc.

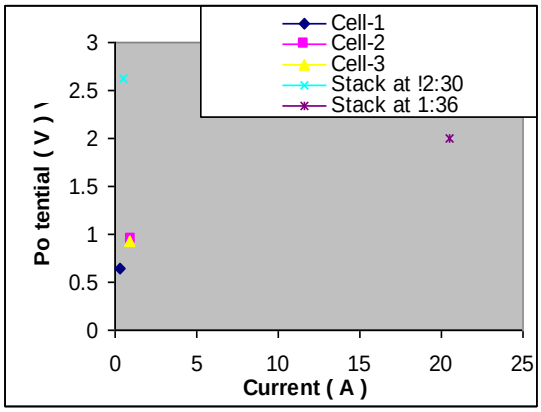

Figure 13: Determination of current–voltage contribution of individual cells in the 3-Cell stack Testing.

Conclusions

1. It has been investigated that by using metallic materials, e.g., copper, aluminum, stainless steel and gold- quately addressed. It was found that pure graphplatted copper, some of the required properties are satisfactory but corrosion, weight and fabrication problems are of considerable attention. On the other hand, by using graphite and graphite composite materials the problem of porosity, conductivity and fabrication cost were adeite could be the ideal candidate for bipolar plate material having good electrical and thermal conductivity, easy machining and resistance to corrosion at all fuel cell operation conditions but two of its properties, i.e, porosity and poor mechanical strength make it unfit as the ideal bipolar plate material. Therefore, by compounding graphite with other polymers, binders and ionomer materials the required properties for bipolar plates can be achieved.

2. The platinum catalyst has been synthesized and successfully used to fabricate MEA. Its efficiency has been found to be encouraging after investigating the polarization curves.

3. The catalytic activities of the catalysts can be measured by employing the smooth platinum electrode method as methanol electro oxidation in 1 M H_2SO_4 also exhibited similar behavior as that in 1 M NaOH, but the curves presented in Tafel plots has given the difference in slope values highlighting the difference in over potential exhibiting the difference in catalytic behavior.

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