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Effect of Humidifier Temperatures on Nafion-XL Membrane Electrode Assemblies (MEA) – An Experimental Study

G. Vasu[1], B. Sreenivasulu[2,], G.V.S. Sarma[3,*], D. Arjun[1], B. Anusha[3], K.V. Ramesh[3]

[1]*Fuel Cells and Renewable Energy Systems, BHEL Corporate R&D Division, Hyderabad-500093, India.*
[2]*Department of Chemical Engineering, GVPCOE(A), Visakhapatnam-530048, India.*
[3]*Department of Chemical Engineering, Andhra University, Visakhapatnam-530003, India*

Abstract

The importance of fuel cell as energy source is known ubiquitously. In this regard, studies were carried out on fuel cell test station employing a new membrane, Nafion-XL by Dupont. Data were obtained on cell voltage, power, efficiency, transient response etc. Two systems have been considered in the present case viz., hydrogen/air and hydrogen/oxygen. Naturally hydrogen/oxygen system proved to be superior than hydrogen/air in terms of performance. Optimum anode and cathode humidification temperatures were obtained experimentally for both the systems. Optimum fuel cell operation temperature is found to be 65°C. Anode humidification temperature is the key parameter that exhibited considerable influence on fuel cell performance in the present studies.

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Keywords: Fuel cell, membrane, humidification temperature, Nafion

1. Introduction

Without sufficient energy the living standards cannot be met in the modern days. The man meets his energy needs from various sources such as fossil fuels, atomic energy, solar and other renewable sources etc. All these sources are associated with one or other form of safety and pollution issues. In this regard fuel cells offer lower safety problems without damaging environment. Further the efficiency that is obtained from other sources is very less because they are mostly governed by Carnot laws, however, the fuel cells yield much higher efficiencies because they are not governed by Carnot laws. They can be used as power sources for remote locations and automobiles. In this way the fuel cells are indispensable in some applications.

[*]Corresponding author: Tel: +91-9441968234; Email: gvssarma@yahoo.com.

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Larmine and Dirks [1] and Barbir [2] compiled the literature pertaining to various aspects of the fuel cell technology. Studies on enhancement of performance of a proton exchange membrane (PEM) fuel cell through reactant gas channel and gas diffusion layer optimization has been carried out by Obayopo et al [3]. This study helps in improving the design of fuel cells. Several studies on water balance, water transport and water management in fuel cells were reported with a variety of available membranes [4,5]. Effect of various parameters on cell performance has been investigated by Abdulla et al [6] and Guvelioglu and Stenger[7]. A close examination of the literature suggests that no study has been carried out on the effects of humidification temperatures on fuel cell performance employing Nafion-XL membrane. In this regard the present work has been taken up.

For the present study PEM fuel cells have been chosen because of their promising potential in future applications. The membrane selected is Nafion-XL made by Dupont, which is a proton conducting membrane that consists of a PTFE-based polymer backbone to which sulfonic acid groups are attached. To the best of the knowledge of the authors, studies utilizing Nafion-XL are not available in the open literature. In this connection the present investigation has been taken up.

2.Experimental

Proton Exchange Membrane Fuel cell test station, which is shown in Fig.1, manufactured by Fuel Cell Technologies Inc., USA was used to carry out the present investigation. The capacity of the test station is 1.2 kW and the test station is equipped with a stack of two cells. For the present experimental study an active surface area of 225 cm^2 was used. The membrane electrode assembly (MEA), consisted of a Nafion XL – Dupont membrane in combination with total platinum loadings of 0.8 mg/cm^2 per electrode. The gas diffusion layers were made of carbon fiber. The MEA positioned between two graphite plates was pressed between two end pressure plates. The graphite plates were grooved with parallel serpentine gas channels. The fuel cell test station can control the fuel cell temperature, humidification temperatures and back pressure on both anode side and cathode side with the help of a computer.

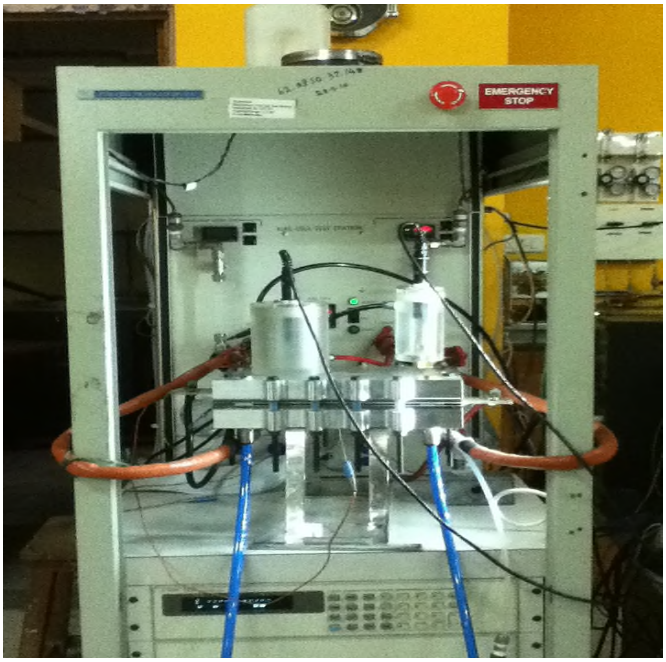

Fig.1. Fuel cell Test station with experimental cell

The reactant gases were humidified by passing through water columns mounted within the test station at back side of the front panel. Gas receives the moisture by passing through the water column, the amount of water carried by the gas is governed by the regulation of water temperature and flow rate of gas, hence control is exercised on the humidification of reactant gases. Fuel cell temperature and humidification temperature were controlled by temperature controller. Also, the test equipment consists of back pressure regulators on each side for anode (hydrogen) and cathode (air/oxygen) separately and were used to regulate the backpressure. This test station also equipped with a computer based application software known as LabVIEW. The computer system was connected to mass flow controllers, which were located prior to humidifiers. The mass flow rates were set and read through the software. The fuel cell polarization curves were obtained from this program as well by controlling the N3300A electronic load, which measures the voltage vs current response of the fuel cell. In addition a humidifier sensor was connected to the inlets of the fuel stack. By this, one can get the values of relative humidity/ dew-point and humidified gas temperatures.

The test station comprised with the following inbuilt features: mass flow controller, anode and cathode bubble humidifiers, electronic load box, temperature controllers, back pressure regulators, provision for operation at constant current, voltage and power mode, pressure indicators, reactant gas preheating, on board hydrogen leak detector, data logging at require time intervals for various variables of interest and automatic shut down and nitrogen purging. The sequence of operations was carried out as per the recommended procedure.

3. Results and discussion

In the present study, experiments were conducted to elucidate the effects of anode and cathode humidification temperatures on cell voltage, power density, cell efficiency for two systems viz., hydrogen/air and hydrogen/oxygen. The performance of these two systems was also compared. Data were also obtained to know the behaviour of the fuel cell over wide range of operating conditions.

3.1. Polarization curve

Fig.2 shows a typical polarization curve for a single cell with hydrogen/air fuel system. The theoretical voltage that is arrived by electrochemical means is 1.23 V [8] which is also shown in the figure. The cell voltage obtained in the present experimental study for one particular case is also presented. It can be noticed that the actual voltage is much smaller than the theoretical voltage. This is because of the voltage losses that appear in the cell operation. These losses are categorized into three types viz., activation polarization losses, ohmic losses and concentration polarization losses. Actual voltage is obtained by subtracting the sum of voltage losses by all these means from theoretical voltage. It is to be understood that the open circuit voltage (OCV) is also less than the theoretical voltage because of the presence of internal currents and crossover losses. However, these losses are insignificant when the fuel cell is set in operation.

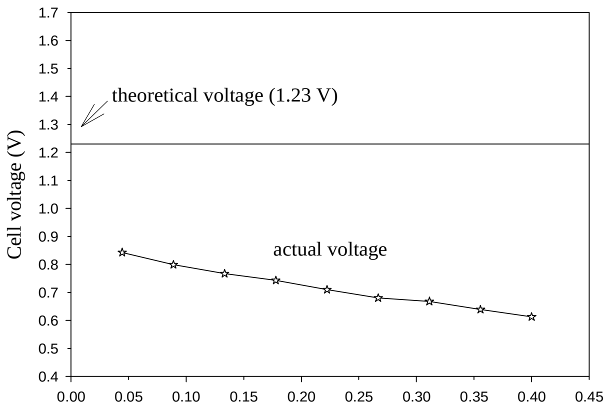

Fig.2. Polarization curve for a single cell when cell temperature is 60°C, anode and cathode temperatures are at 50°C, hydrogen and air flow rates are at 2 and 10 lpm respectively

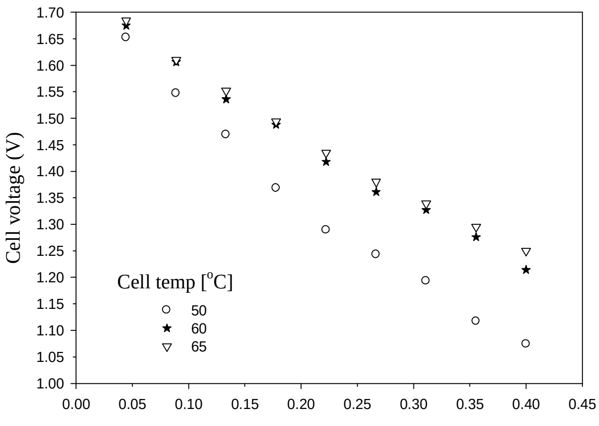

Fig.3. Effect of fuel cell temperature

3.2. Effect of fuel cell temperature

An increase in operating temperature of the fuel cell generally leads to improved cell performance. However, for every fuel cell system, there exists an optimum operating temperature at which the cell performance would be at its peak value. To determine this temperature, in the present investigation, experiments were carried out to find out the influence of fuel cell temperature on the performance of the cell. These studies consisted of varying the fuel cell temperature from 50 to 65°C with the anode and cathode humidification temperatures kept at 50°C. The volumetric flow rates of hydrogen (at anode) and air (at cathode) are kept constant at 2 and 6 lpm respectively. The polarization curves thus obtained were shown presented in Fig.3.

An examination of the polarization curves in this graph indicates that the cell voltage is higher for the highest value fixed for the cell temperature within the range of temperatures employed in the present case. The reason for better performance at higher temperatures can be attributed to the enhanced mass transport properties as a result of increased exchange current density. A close inspection of the polarization curves of this figure shows that as the cell temperature is increased from 50 to 65°C there is a clear indication of voltage gain with increased temperature. Further the voltage gain with increased temperature is small at lower current density and increased gradually with increase in current density and became more prominent at higher current densities. Therefore, in the present study, peak performance is observed for a cell temperature of 65°C. Hence 65°C is taken as the operation temperature for the fuel cell.

3.3. Effect of electrode humidification temperatures on cell voltage in H_2/Air system

Experiments were carried out to investigate the effect of anode and cathode humidifier temperatures on cell voltage by employing constant flow rates of hydrogen and air at 2 and 6 lpm respectively. The fuel cell temperature is maintained constant at 65°C.

3.3.1. Effect of anode humidification temperature

The polarization curves obtained at three different anode humidification temperatures viz., 40, 50 and 60°C by maintaining a constant cathode temperature of 40°C were shown in Fig.4a. It can be observed that all three plots are linear and more or less parallel to each other. This behaviour indicates that the variation in electrical resistance is very insignificant. It is well known that the electrical resistance of the fuel cell contributes to the ohmic losses. Since the variation in electrical resistance is negligible, the variation in ohmic losses are also negligible.

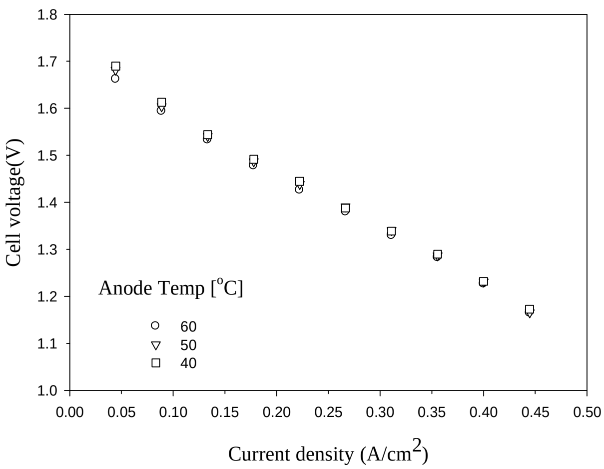

Fig.4a. Effect of anode humidification temperature when the cathode humidification temperature is fixed at 40°C

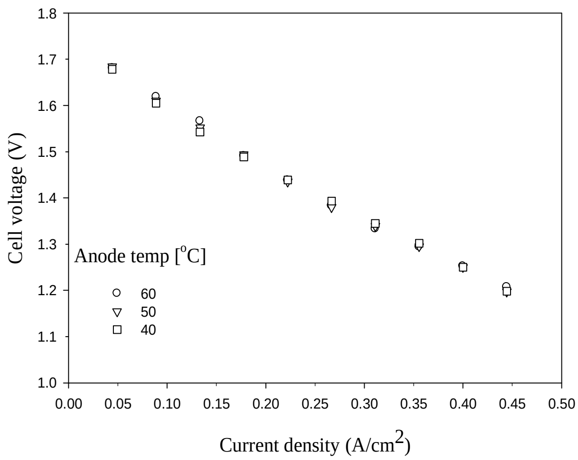

Fig.4b. Effect of anode humidification temperature when the cathode humidification temperature is fixed at 50°C

When examined for the influence of temperature within the entire range of current density considered for this case, it can be observed that higher the anode temperature lower the cell voltage. Also lower the anode temperature, higher the cell voltage. This observation is conspicuous in the entire range of current densities. In this case two effects influence the resulting cell voltage. These are electro-osmotic drag that pulls water towards cathode and water generation at cathode. Explanation for the observed behaviour can be made in the following way. Since the cathode temperature is maintained constant, the water generation at cathode is same in all cases. However, water travels from cathode to anode, which is called as back diffusion. But, the protons moving from anode to cathode drag the water molecules towards cathode which is termed as electro-osmotic drag. Under similar conditions of current densities irrespective of anode side humidifier temperature, the electro-osmotic drag (number of water molecules carried by H^+ in the form of H_3O^+) remains same, whereas the water transport from cathode to anode by back diffusion would decrease due to increase of water concentration at anode side with increase in anode humidifier temperature. This phenomenon of water transport would result in increase of water concentration on cathode side which in turn leads to blockage of some catalyst active sites that can lead to decrease of cell voltage. Hence, with increase in anode temperature a decrease in cell voltage is observed.

Similarly one more graph is drawn for constant cathode humidification temperature of 50°C and shown as Fig.4b. An inspection of the plots of Fig.4b shows that at the cathode humidification temperature of 50°C, when the anode humidification temperature is varied from 40 to 60°C, higher cell voltage is slightly seen for the anode humidification temperature of 40°C. This trend is also similar to the trend discussed in connection with Fig.4a. From remaining data (graphs not shown here) also it can be clearly seen that the cell voltage is higher for the lower anode humidification temperature of 40°C when the cathode humidification temperature is maintained constant at 60°C[9]. It can be inferred from the observations that, the cell voltage is predominantly depends on the cathode humidification than the anode humidifier temperature.

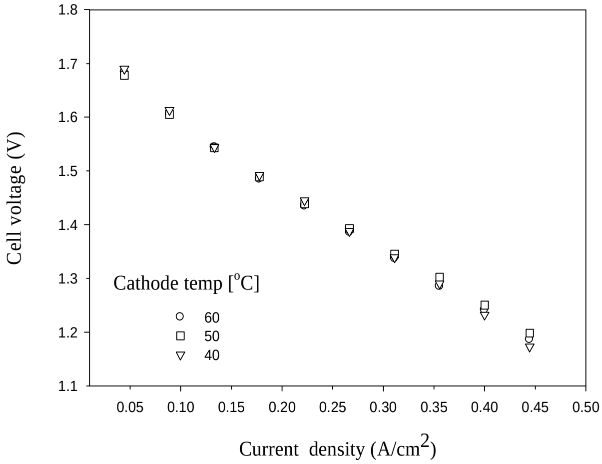

Fig. 5a. Effect of cathode humidification temperature when anode humidification temperature is at 40°C

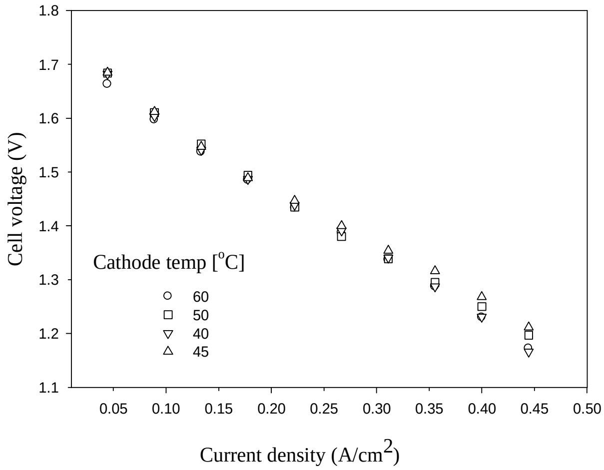

Fig.5b. Effect of cathode humidification temperature when anode humidification temperature is at 50°C

3.3.2. Effect of cathode humidification temperature

The polarization curves obtained at three different cathode humidification temperatures viz., 40, 50 and 60°C by maintaining a constant anode temperature of 40°C were shown in Fig.5a. It can be observed that all three plots are more or less linear in the present case also indicating that the variation in ohmic losses is negligible. Further it can be seen from Fig.5a that two different trends for cell voltage can be observed; one at lower current density side and another at higher current density side. When inspected at lower current density side, one can notice that all points are clustered together indicating no effect of cathode humidification temperature. This is because at lower current densities the water generation rate is such that the catalyst layer is maintained at saturation level and hence no variation in cell voltage with changes in cathode humidification temperature. However, at higher current density side, it can be noticed that higher voltage gain is obtained for the cathode humidification temperature of 50°C. For both cathode humidification temperatures of 40°C and 60°C, the cell voltage obtained was less. The reason for this behavior can be explained in the following way. At cathode humidification temperature of 40°C, the membrane is not completely hydrated where as at 60°C, some fraction of cathode active sites are possible to get occupied with the excessive water carried by inlet air was more because there is no change in the humidification temperature of anode. Therefore, at cathode humidification temperature of 50 °C only better hydration of catalyst layer occurred and hence higher value for cell voltage is recorded. Fig.5b shows similar graph plotted for the constant anode humidification temperature of 50°C when cathode humidification temperatures are varied as 40, 45, 50 and 60°C. The trends in this graph are also similar to Fig.5a and highest voltage gain in high current density range is obtained at a cathode humidification temperature of 45°C. Similar observations can be made from the graph (not shown here) which is drawn for the constant anode humidification temperature of 60°C and the trends are also same. Voltage gain is noticed for the cathode humidification temperature of 50°C.

3.3.3. Optimum electrode humidification temperatures for H_2 / Air reactants

For all combinations of anode and cathode humidification temperatures employed in the present case with hydrogen/air system, the cell voltage vs. current density plots were drawn and shown in Fig.6a.

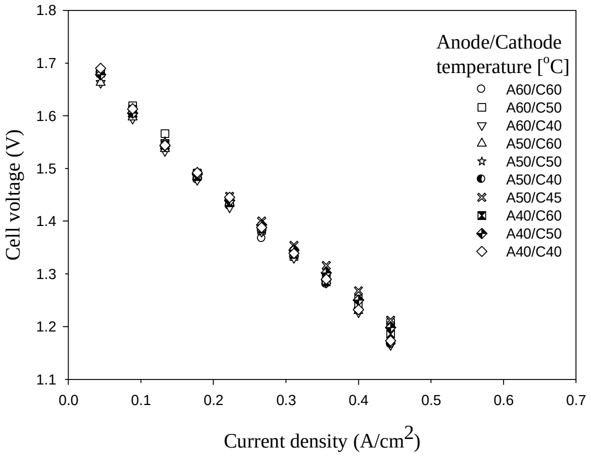

Fig.6a. All humidifier temperatures for the case of H_2/Air system

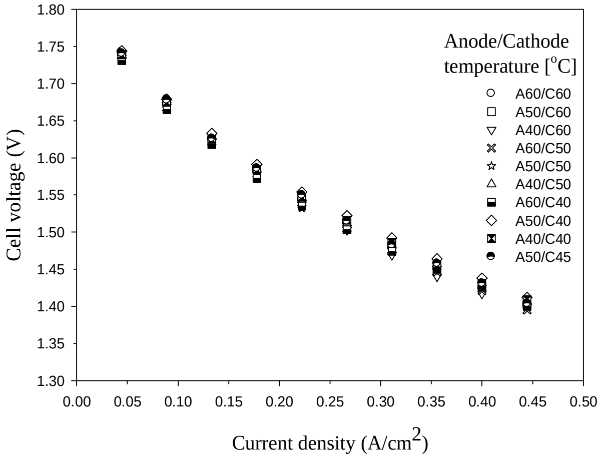

Fig.6b. All humidifiers temperatures for the case of H_2/O_2 system

A close examination of the plots of this figure reveals that at lower current density side, voltage gain is seen for an anode temperature of 40°C and a cathode temperature of 40°C. At higher current density side, the voltage gain is obtained for an anode humidification temperature of 50°C and a cathode temperature of 45°C. Generally the fuel cell is operated in the higher current density range. Hence the optimum humidification temperatures for anode and cathode are 50°C and 45°C respectively while the stack is operated at 65 °C.

3.4. Effect of electrode humidification temperatures on cell voltage in H_2/O_2 system

Experiments were carried out to investigate the effect of anode and cathode humidifier temperatures on cell voltage by employing constant flow rates of hydrogen and oxygen at 2 and 1.2 lpm respectively. The fuel cell temperature is maintained constant at 65°C. Studies similar to H_2/Air system are also carried out with H_2/O_2 system. For all combinations of anode and cathode humidification temperatures employed in the present case with hydrogen/oxygen system, the cell voltage vs. current density plots were drawn and shown in Fig.6b.

A close examination of the plots of this figure reveals that at lower current density side, voltage gain is seen for an anode temperature of 50°C and a cathode temperature of 40°C. This is almost uniform in the entire range of current density employed. Thus the optimum humidification temperatures for anode and cathode are 50°C and 40°C respectively while the stack is operated at 65 °C.

3.5. Comparison of H_2/Air and H_2/O_2 systems

It can be anticipated that the H_2/O_2 system yields better cell voltage, power and efficiency in comparison with H_2/Air system because in air the presence of oxygen is only 21% by volume. Hence the inert nitrogen occupies some portion of the active catalyst and also causes a decrease in the diffusion rates of the reactants. Therefore, better performance can be expected in the case of H_2/O_2 system. Fig.7 shows the plots drawn for cell efficiency against current density for both the systems. It can be observed for the plots of the figure that the cell efficiency is higher for hydrogen/oxygen system for the entire range of current density employed in the present study. Further the difference got increased towards the higher current density end. The hydrogen / oxygen system reported a higher efficiency of 7% at lower end and 23 percent at higher end. Therefore, the hydrogen/oxygen system may be preferred from this point of view. However, the cost of oxygen plays vital role in choosing the system. Therefore, the system may be chosen based on the economics of the operation.

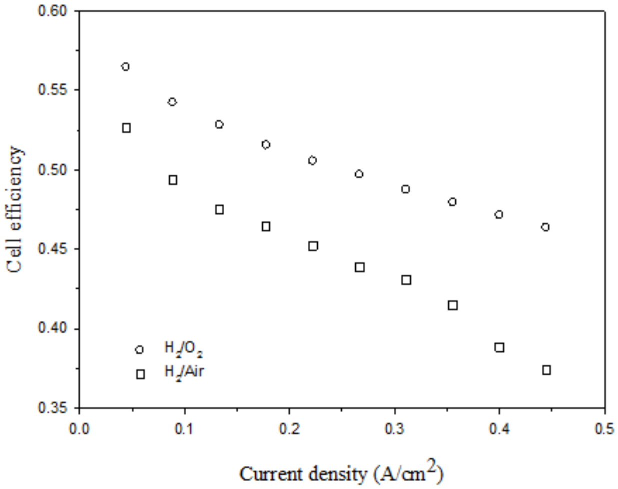

Fig.7. Comparison of cell efficiency (Anode = 50^{o}C; Cathode = 50^{o}C)

4. Conclusions

Fuel cell has been operated for a period of 700 hours, and about 3500 data points were obtained. Studies were carried out on the effects of various pertinent parameters on fuel cell performance.

It was observed from various performance curves and operating regimes, optimal cell voltage is seen at a fuel cell operating temperature of 65^{o}C. The cathode humidification temperature has not exhibited any visible influence on cell voltage in case of both the systems within the range of cathode temperatures employed. This can be attributed to complete humidification of the cathode catalyst layer. The anode humidification temperature has shown remarkable influence on cell voltage in case of both the systems of oxygen and air reactants. Only at medium temperatures better hydration of the anode catalyst layer is observed. Voltage gain is seen for anode humidification temperature of 50^{o}C and cathode humidification temperature of 45^{o}C for the hydrogen/air system. Voltage gain is seen for anode humidification temperature of 50^{o}C and cathode humidification temperature of 40^{o}C for the hydrogen/oxygen system. No visible influence of anode and cathode humidification temperatures was seen on power density and cell efficiency in case of both the systems. Due to the fact of excess air flow rate, humidification requirement for cathode side reactants is more in case of air is used as the reactant feed gas instead of oxygen for same current density. The reason could be the water carrying by air is more as the flow rate of air is multiple times of oxygen flow rate under similar conditions of operating current. The excess flow rate of air leads to drying of membrane, therefore requirement water supply is more which was supplied in the form of higher relative humidity by increasing the humidifier temperature.

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