EFFECT OF OPERATING PARAMETERS ON THE PERFORMANCE OF PEM FUEL CELL WITH VARIOUS FLOW FIELD GEOMETRIES – A THEORETICAL STUDY

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Abstract

Simulations on effect of operating parameters such as temperature, pressure, humidity and anode humidification temperatures have been carried out to study the performance of Proton Exchange Membrane Fuel Cell (PEMFC) with various flow field geometries like parallel, interdigitated and 4-serpentine. A theoretical analysis is carried out in FLUENT on single PEMFC. The PEMFC simulated is validated with an experimental data and fuel cell performance is improved with an increase in temperature (50^0 C to 70^0C), increase in operating pressure (1 to 3 atm), increase in humidity (up to 65%) and decreases with increasing the anode humidification temperature (60 ^{0}C to 80 ^{0}C). The Interdigitated flow field is better than 4-Serpentine and 4-Serpentine flow field is better than parallel flow fields.

Index Terms: *PEM Fuel cell, Fluent, Cell temperature, Performance, Anode Humidification temperature*

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1. INTRODUCTION

Polymer electrolyte membrane fuel cell (PEMFC) was the most promising system among several different kinds of fuel cells due to their various advantages such as easy start-up, room temperature operation, no liquid electrolyte, and high current density. To achieve high current density, the optimal operating conditions need to be identified for fuel cell systems in addition to design parameters such as membrane, catalyst particle size, quantity, and nature of gas diffusion layers. There were many variables in the operation of fuel cell systems, viz., fuel cell temperature, reactant pressure, reactant flow, relative humidity and load. Fuel cell modelling is also received much attention over the last 20 years in an attempt to better understand the phenomena occurring within the PEM fuel cell. Parametric models help the engineers and designers to predict the performance of the fuel cell given geometric parameters, material properties and operating conditions. These theoretical models are compared with the experimental data.

Jer-Huan Jang et al. [1] developed a three-dimensional numerical model of the PEMFCs with conventional flow field designs (parallel flow field, Z-type flow field, and serpentine flow field) to investigate the performance and transport phenomena in the PEMFCs. For the conventional flow fields, the cell performance can be enhanced by adding the corner number, increasing the flow channel length, and decreasing the flow channel number. The cell performance of the serpentine flow field is the best, followed by the Z-type flow field and then the parallel flow field.

Jianlu Zhang et al. [2] studied the effect of Relative Humidity (RH) on PEMFC performance was studied at elevated temperatures under ambient backpressure using Nafion-based Membrane Electrode Assembly. The water balance inside a fuel cell was analysed and several equations were introduced as functions of fuel cell gas-stream inlet and outlet pressures, inlet RH, temperature, pressure drops across flow channels, and reactant partial pressures.

Jason P. Kloess et al. [3] investigated on both numerical simulation and experimental tests to show the effects of two new flow channel patterns on fuel cell performance. These bio-inspired designs combine the advantages of the existing serpentine and interdigitated patterns with inspiration from patterns found in nature. From the numerical simulation, it was found that there is a lower pressure drop from the inlet to outlet in the leaf or lung design than the existing serpentine or interdigitated flow patterns.

Alfredo Iranzo et al. [4] developed a Computational Fluid Dynamics (CFD) model for a 50 cm^2 fuel cell with parallel and serpentine flow field bipolar plates, and its validation against experimental measurements. The numerical CFD model was developed using the commercial ANSYS FLUENT software, and the results obtained were compared with the experimental results in order to perform a model validation.

B. Sreenivasulu [5] studied the experimental and theoretical studies on single PEMFC by operating the cell at various system conditions such as temperature, pressure, humidity and different flow field plates (parallel, 4 serpentine) to illustrate the effects of the system conditions on voltage and power produced by the cell.

Hence, this paper is intended to carry out the theoretical studies to analyse the effects of various parameters such as temperature, pressure, humidity, anode humidification temperature on the performance of PEMFC. The theoretical studies are carried out on single PEMFC using Fluent 6.3.

2. FORMULATION OF PROBLEM

A three dimensional CFD model of the PEMFC shown in Fig. 1 consists of cathode and anode gas flow channels and the membrane electrode assembly. The active area of the membrane electrode assembly is 94 cm^2.

The flow of hydrogen and oxygen in a fuel cell takes place in the channel formed by a flow field plate and a carbon paper, which serves as gas diffusion layer. The flow channel contains a number of bends and/or dead ends to facilitate diffusion of the gas through the carbon paper (GDL) while the gas passes through the channel. The single fuel cell containing the membrane electrode assembly with parallel, interdigitated and 4 Serpentine flow field plates are simulated using FLUENT software.

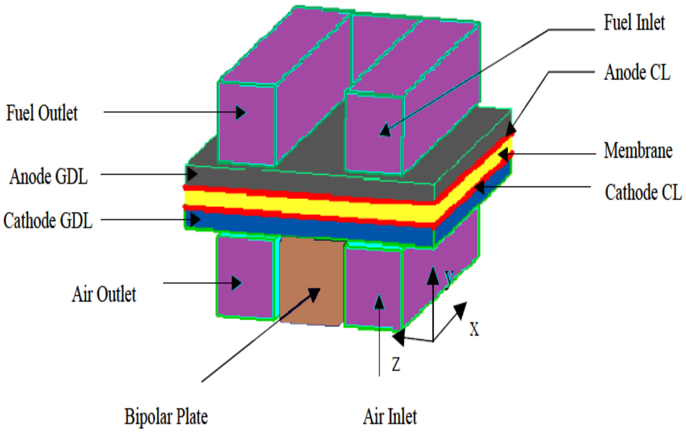
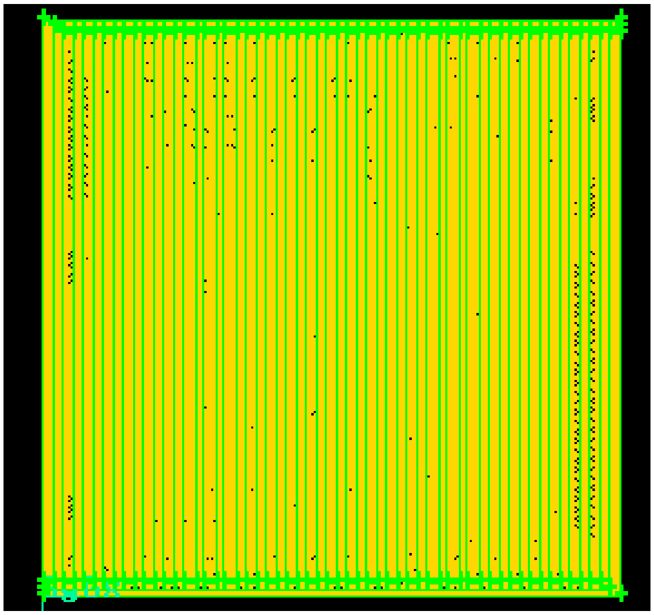
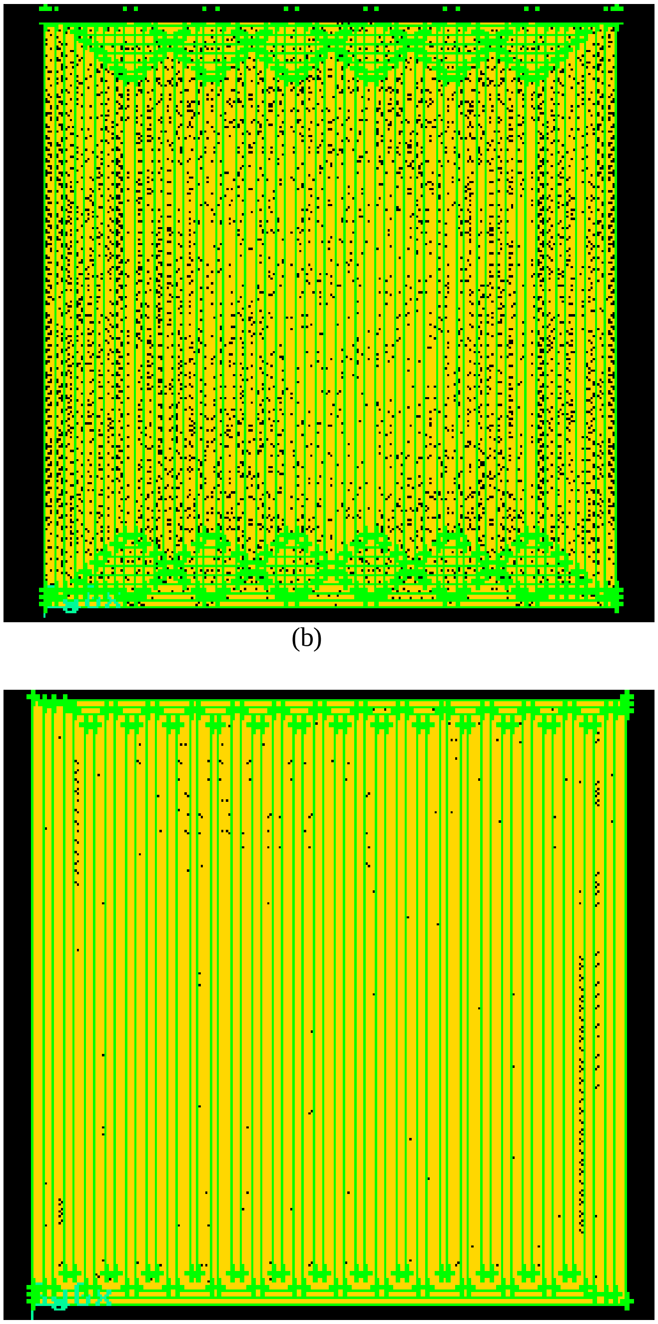


Fig-1: Three-dimensional computational domain (Components are not to scale).

The whole computational domain is a channel (viz. Parallel, Interdigitated, 4-Serpentine), anode and cathode electrodes, catalyst layers and membrane. All the components are meshed and assembled in GAMBIT. The three-dimensional meshed geometry of PEM fuel cell with various flow fields (viz. Parallel, Interdigitated, 4-Serpentine) created in the GAMBIT are shown in Figures 2a, 2b and 2c.



(a)



(b)

(c)

Fig-2: 3-D (meshed) geometry of (a) Parallel Flow Channel b) 4-Serpentine Flow Channel (c) Interdigitated Flow Channel

The special add-on module for fuel cell embedded in FLUENT solves the problem considering all the relevant equations of flow, mass and heat transfer. This software solves numerically the equations of continuity, momentum balance, energy balance and diffusion (component material balance) by finite volume method in the form of SIMPLE algorithm and by pressure correction method. The flow chart of the solution procedure is shown in Fig. 3.

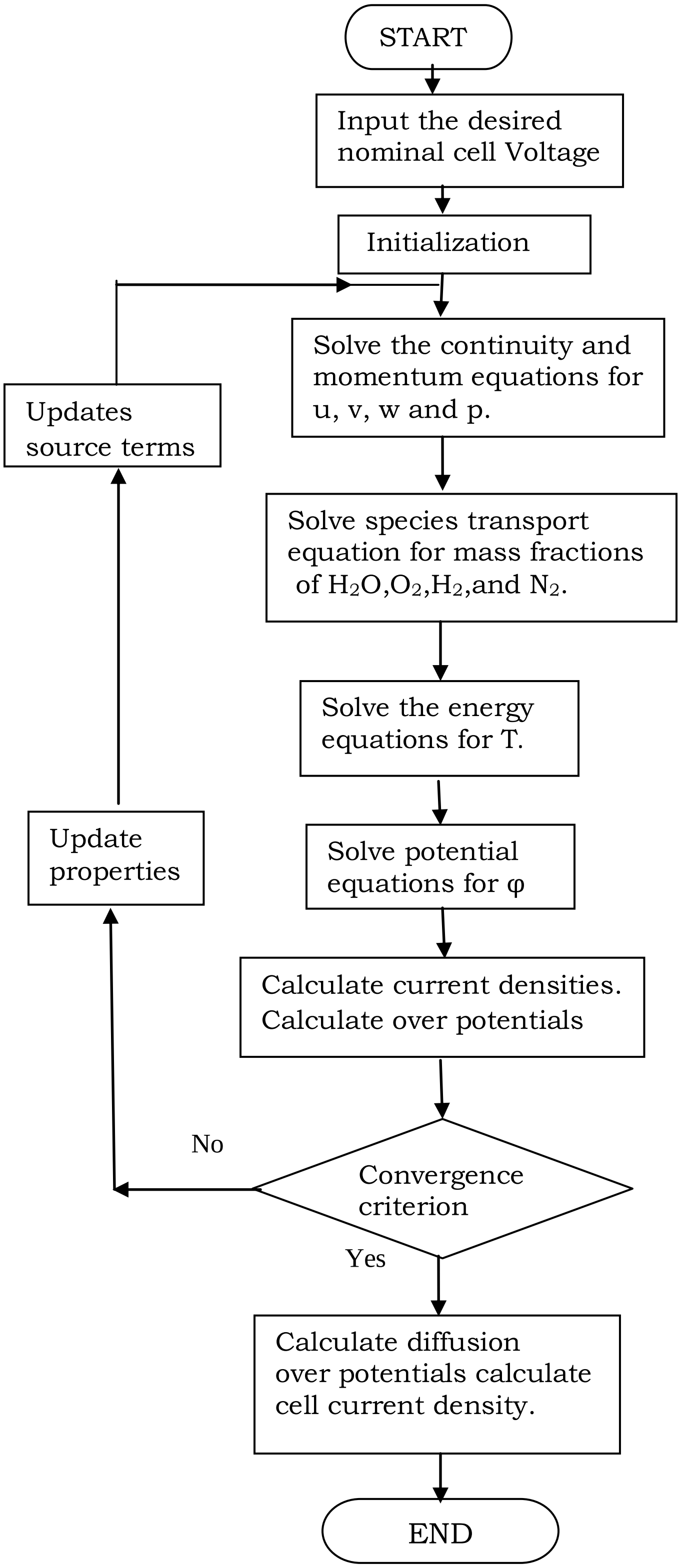


Fig-3: Flow chart of the solution procedure

3. METHODOLOGY

Stringent numerical tests are performed to ensure that the solutions are independent of the grid size. A computational mesh of 200270 computational cells is found to provide sufficient spatial resolution. The solution begins by specifying a cell voltage for calculating the inlet flow rates at the anode and cathode sides. An initial guess of the activation over potential is obtained for the given cell voltage using the Butler-Volmer equation. The local activation over potentials is updated after each global iterative loop. Convergence criteria are then performed on each variable and the procedure is repeated until convergence is achieved.

Choosing the right modeling parameters is important in establishing the base case validation of the model against experimental results. Since the present model accounts for all basic transport phenomena by virtue of three-dimensionality, a proper choice of the modeling parameters will make it possible to obtain good agreement with experimental results from a real fuel cell. It is important to note that this model accounts for all major transport processes and the modeling domain comprises all the elements of a complete cell.

4. RESULTS AND DISCUSSION

The performance characteristics of the fuel cell based on a certain parameter can be obtained by varying that parameter while keeping all other parameters constant. Results obtained from these parametric studies will allow in identifying the critical parameters on the fuel cell performance. The fuel cell performance at various operating conditions is analyzed using the polarization curves and power curves for three types of flow geometries of the flow channels like parallel, 4-serpentine and interdigitated. Theoretical results are obtained for three different flow geometries, parallel, 4-serpentine and interdigitated of the flow channel for the system parameters like temperature, anode humidification temperature, humidity and pressure on fuel cell performance and discussed in the following sections.

The theoretical results are obtained for the 4-serpentine geometry flow channel at 333 K, 1 atm, 100% RH, H_2 & O_2 flow rate 0.3 lpm each and are compared with the experimental data shown in Fig. 4. The obtained theoretical results show the good agreement with the experimental data.

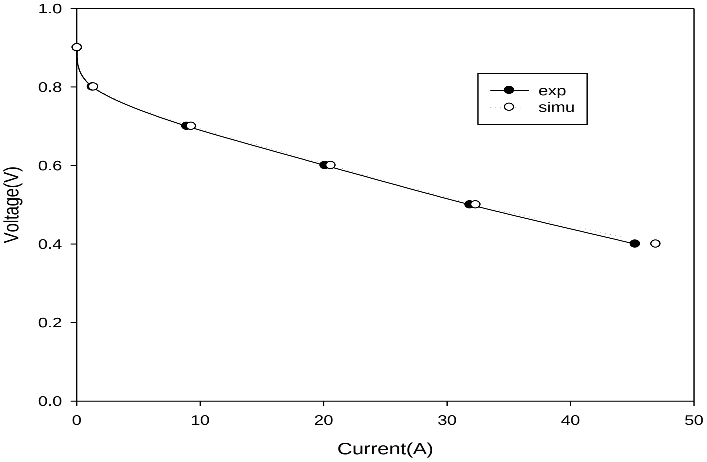


Fig-4: Comparison of simulation results with the experimental data at 333 K, 1 atm, 100% RH, H_2 & O_2 flow rate 0.3 lpm

4.1 Effect of Temperature

Change in cell temperature will affects all transport phenomena and electrochemical kinetics inside the fuel cell. In these study two types of geometries, parallel and interdigitated flow channel are considered by putting the pressure and electrode porosity are kept constant at 1 atm. and 0.5 respectively and the theoretical results are obtained by varying the cell temperatures from 50^0C to 70^0C.

The polarization curve of the cell at different operating temperatures is shown in Fig. 5 and 6 for the parallel and interdigitated flow field respectively. It is observed that the fuel cell performance is improved with an increase in temperature. The performance is better in all regions along the polarization curve however the gain is observed to be larger in the ohmic overpotential region than the activation overpotential region. This is due to increase of gas diffusivity, exchange current density and membrane conductivity at higher temperature.

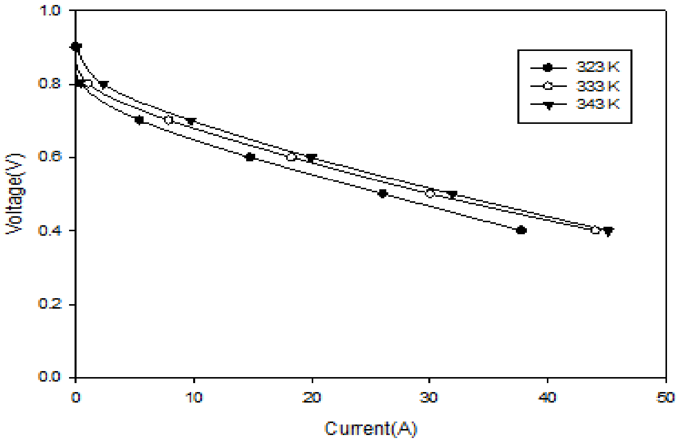


Fig-5: Effect of temperature on cell performance (V-I curve) in parallel flow field at 1 atm, 100% RH, H_2 & O_2 flow rate 0.3 lpm

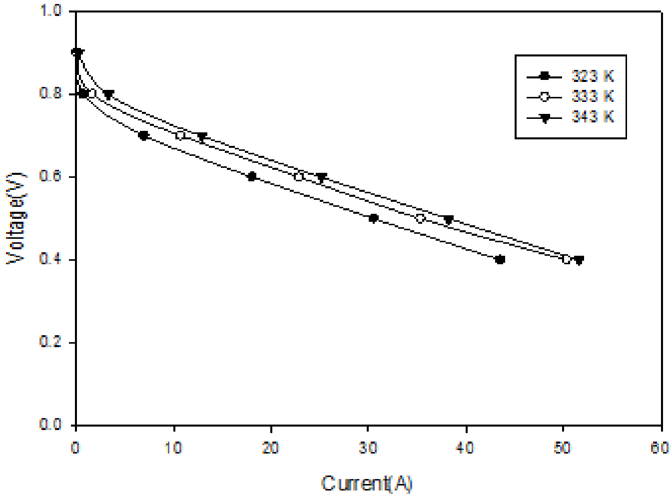


Fig-6: Effect of temperature on cell performance (V-I curve) in interdigitated flow field at 1 atm, 100% RH, H_2 & O_2 flow rate 0.3 lpm

4.2 Effect of Pressure

Pressure is another operating parameter that has large effects on fuel cell performance. In this parametric study, the cell operating temperature and electrode porosity are kept at 343 K and 0.5 respectively, while the pressure is varied from 1 atm. to 3 atm. in parallel flow field and interdigitated flow field.

The polarization curve of different cell operating pressures is shown in Fig. 7 and 8 for the parallel and interdigitated flow fields respectively. Since the saturation pressure remains constant for constant operating temperature, the mole fraction of water vapor decreases with increase in total pressure. The mole fraction of oxygen increases with increase in operating pressure. As the operating pressure is increased from 1 atm. to 3 atm., the fuel cell performance also increases. Therefore, higher cell operating pressure should be selected to improve the cell performance.

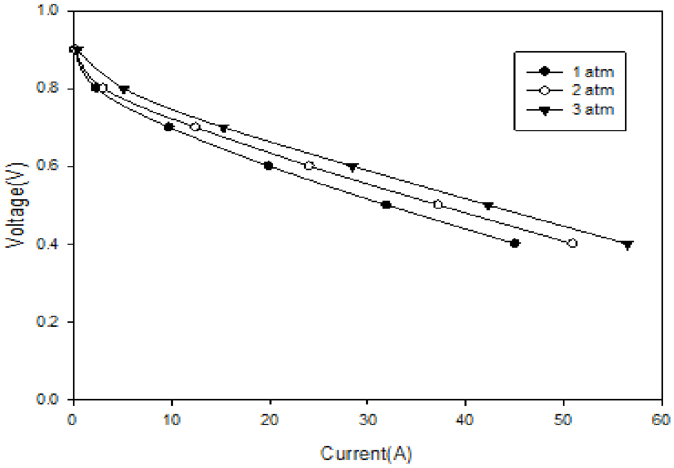


Fig-7: Effect of pressure on cell performance (V-I curve) in parallel flow field at 343 K, 100% RH, H_2 & O_2 flow rate 0.3 lpm.

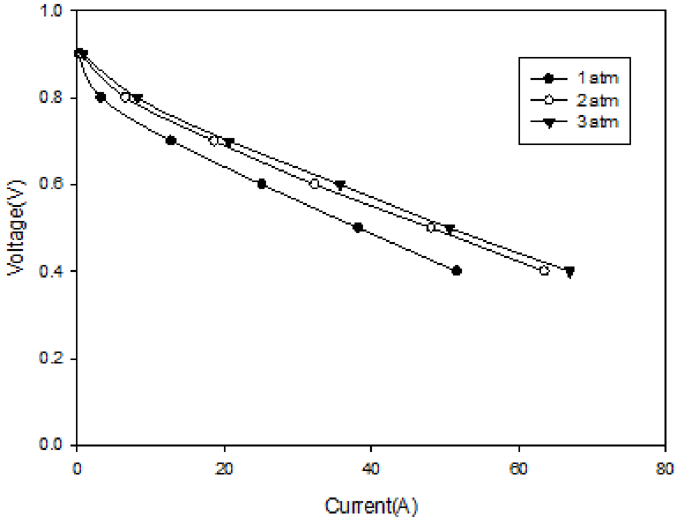


Fig-8: Effect of pressure on cell performance (V-I curve) in interdigitated flow field at 343 K, 100% RH, H_2 & O_2 flow rate 0.3 lpm.

4.3 Effect of Gas Humidity

The effect of reactant stream humidity on the cell performance is shown in Fig. 9 and 10 in the parallel and interdigitated flow fields. It is observed that the performance of fuel cell increases with humidity up to 65% and there is no further improvement in the performance with an increase in humidity above 65%. Below 65% of reactant stream humidity the voltage drop occurs due to the availability of less amount of water at the electrolyte membranes of the fuel cell. These membranes must maintain a minimum level of moisture in order to properly conduct ions. Further it is observed that at higher currents the cell performs better at lower humidities. This is due to the fact that the formation of water is more at higher currents.

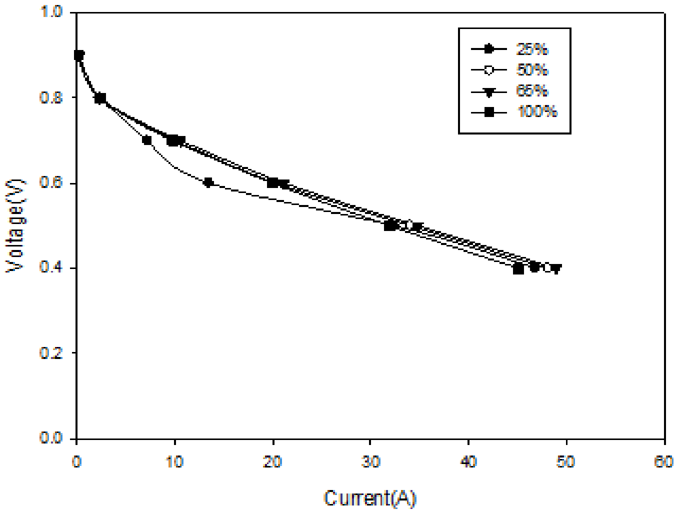


Fig-9: Effect of humidity on cell performance (V-I curve) in parallel flow field at 343 K, 1 atm, H_2 & O_2 flow rate 0.3 lpm.

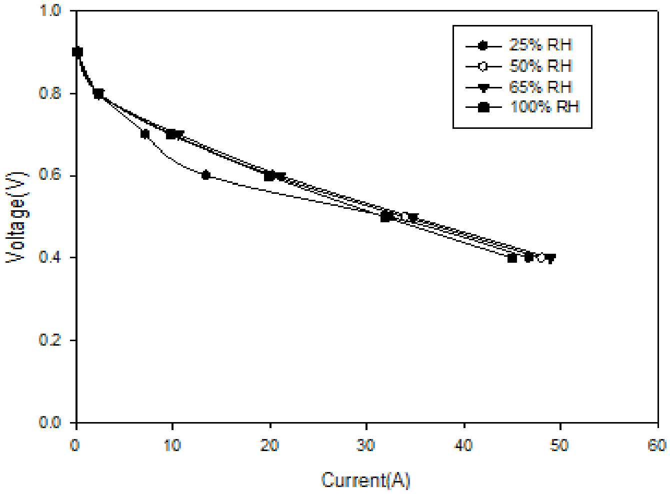


Fig-10: Effect of humidity on cell performance (V-I curve) in interdigitated flow field at 343 K, 1 atm, H_2 & O_2 flow rate 0.3 lpm.

4.4 Effect of Anode Humidification

In order to study the humidification effect, the results are obtained for the same system by varying the anode humidification temperature of the inlet fuel from 60 ^{0}C – 80 ^{0}C at a constant cell temperature of 70 ^{0}C. The polarization curve for these results is shown in fig. 11 and 12. It is observed that the cell performance decreases with increasing the anode humidification temperature from 60 ^{0}C – 80 ^{0}C. This is due to the decrease of partial pressure of Hydrogen at the anode with the increase of anode humidification temperature.

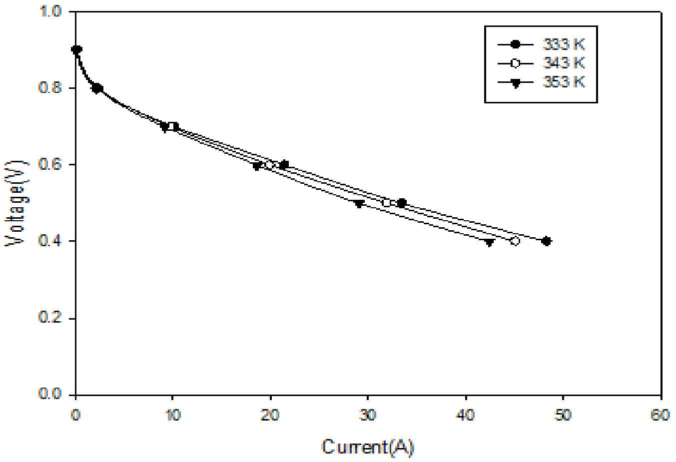


Fig-11: Effect of anode humidification temperature on cell performance (V-I curve) in parallel flow field at cell temperature 343 K, 1 atm, 100% RH, H_2 & O_2 flow rate 0.3 lpm.

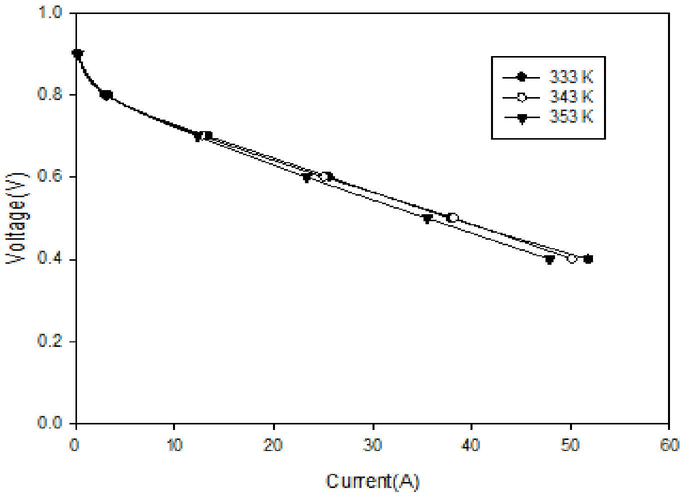


Fig-12: Effect of anode humidification temperature on cell performance (V-I curve) in interdigitated flow field at cell temperature 343 K, 1 atm, 100% RH, H_2 & O_2 flow rate 0.3 lpm

4.5 Channel Effect

Channel effect has an important role on the cell performance of a PEMFC. The obtained theoretical results for the three geometries, parallel, 4-serpentine and interdigitated flow channels at cell temperature 343K, pressure 1 atm, humidity 65%

and Hydrogen and oxygen flow rates 0.3 lpm each are shown in the fig 13. It is observed that in the interdigitated flow field gives the better performance than the parallel and 4-serpentine flow fields since the diffusion is more in the case of interdigitated flow field when compared to the other channels (Parallel, 4-serpentine) due to presence of dead ends, (Availability of gas concentrations is more at the respective sides). It is also observed that in the 4-serpentine channels, diffusion is more compared with parallel channel due to presence of more bends and the residence time. In the parallel channel, the concentration of gases at the catalyst surfaces (anode and cathode) is less compared to other channels (4-serpentine and interdigitated) due to less residence time.

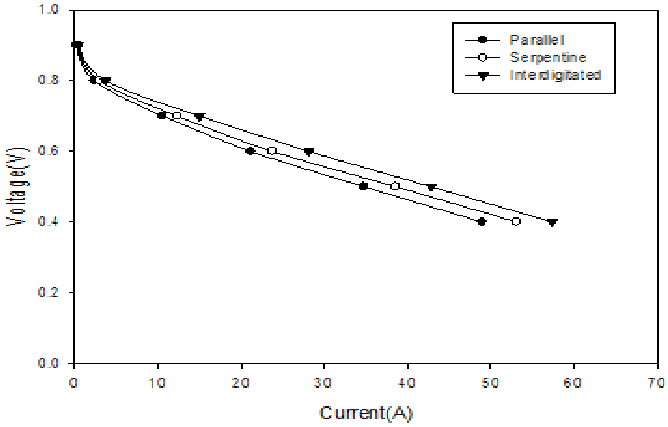


Fig-13: Effect of channel on cell performance (V-I curve) at 343 K, 1 atm, 65% RH, H_2 & O_2 flowrate 0.3 lpm.

5. CONCLUSIONS

- It is observed that the fuel cell performance is improved with an increase in temperature from 50^0C to 70^0C. This is due to increase of gas diffusivity, exchange current density and membrane conductivity at higher temperature.
- As the operating pressure is increased from 1 atm. to 3 atm., the fuel cell performance also increases due to increase in inlet concentration of oxygen.
- It is also observed that the performance of fuel cell increases with humidity up to 65% and there is no further improvement in the performance with an increase in humidity above 65%.
- The cell performance decreases with increasing the anode humidification temperature from 60 ^{0}C – 80 ^{0}C due to the decrease of partial pressure of Hydrogen.
- Among the three flow fields configurations (i.e parallel, 4-serpentine, interdigitated) the interdigitated flow field gives the better cell performance than the parallel and 4-serpentine flow fields due to more diffusion.

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