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Effect of Flow Field Geometries on the Performance of Single Cell PEM Fuel Cell

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Abstract: A comprehensive 3-D computational model for PEM (Proton Exchange Membrane) fuel cell with active area of 25 cm^2 has been developed. The developed model has been validated with published experimental results. This model is used to study the effects of several operating parameters on the performance of PEM fuel cell with two flow field geometries like serpentine and interdigitated. This model has been programmed using FLUENT software. Simulations of several operating parameters like temperature, pressure, relative humidity, anode and cathode humidification temperatures have been carried out for these two flow field geometries. The simulation results are presented in the form of polarization and power curves which shows the effect of various operating parameters on cell performance.

Keywords: Cell performance, Cell temperature, Flow field geometries, PEM fuel cell

1. INTRODUCTION

Fuel cell is an electrochemical device which converts chemical energy directly into electricity. Over the past decades, much attention has been focused upon the research and development of PEM fuel cells as power sources for stationary and portable applications because of their high energy conversion efficiency and near-zero pollutant emission.

The heart of a fuel cell is a polymer, proton-conductive membrane. On both sides of the membrane there is a porous electrode. The electrodes must be porous because the reactant gases are fed from the back and must reach the interface between the electrodes and the membrane, where the electrochemical reactions take place in the so-called catalyst layers, or more precisely, on the catalyst surface. The multilayer assembly of the membrane sandwiched between the two electrodes is commonly called the membrane electrode assembly or MEA. The MEA is then sandwiched between the collector/separator plates "collector" because they collect and conduct electrical current and "separator" because in multi cell configuration they separate the gases in the adjacent cells. At the same time, in multi cell configuration they physically/electrically connect the cathode of one cell to the anode of the adjacent cell, and that is why they are also called the bipolar plates. They provide the pathways for flow of reactant gases (so-called flow fields), and they also provide the cell structural rigidity.

Santarelli and Torchio [1] (2007) explained the behaviour of a PEM fuel cell with variation of the values of six operation variables: cell temperature, anode flow temperature in saturation and dry conditions, cathode flow temperature in saturation and dry conditions and reactants pressure. The fuel cell employed for the experiments is a single PEM fuel cell with a 25Cm^2 Nafion 115 membrane. An increase in the reactant saturation temperature also leads a better performance, especially in the case of low and medium loads. With an increase of the reactant operating pressure, the maximum of the power curve shifts to higher current densities, and this can be linked to the corresponding shift of the limiting current density. The behaviour of the cell was analyzed and discussed using some formulations that describe different cell phenomena.

M. ELSayed Youssef et al. [2] (2010) developed a lumped model for PEM fuel cell based on linear algebraic equations. This model is used to study the effects of several operating and design parameters on fuel cell performance such as input temperature, pressure, stiochometric ratio, membrane thickness and gas diffusion layer thickness.

Baschuk and Xianguo [3] (2009) developed a model to an isothermal, steady state, 2-D PEM fuel cell. Their results show that the length of the gas flow channel has significant effect on the current production of the PEM fuel cell, with a longer channel length having a lower performance relative to a shorter channel length. This lower performance is caused by a greater variation in water content within the longer channel length.

Ramousse et al.[4] (2005) presented a fuel cell model that takes into account gas diffusion in the porous electrodes, water diffusion and electro-osmotic transport through the polymeric membrane and heat transfer in the membrane electrodes assembly and bipolar plates. This model is constructed by combining independent descriptions of heat and mass transfers in the cell with a third description of coupled charge and mass transfers in the electrodes.

Wei-Mon Yan et al. [5] (2006) studied experimentally on the influences of various operating conditions including cathode inlet gas flow rate, cathode inlet humidification temperature, cell temperature, etc. on the performance of PEM fuel cells with conventional flow field and interdigitated flow field. Experimental results show that the cell performance is enhanced with increases in cathode inlet gas flow rate, cathode humidification temperature and cell temperature.

B. Srinivasulu [6] (2011) 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 analysis for a 3-D computational PEM fuel cell model in FLUENT software and to study the effects of various operating parameters such as temperature, pressure, relative humidity, anode and cathode humidification temperature on the cell performance for serpentine and interdigitated flow fields.

2. FORMULATION OF A PROBLEM

A three- dimensional CFD model of the PEM fuel cell consists of bipolar plates (or flow fields), gas diffusion layer, catalyst layer and membrane is shown in figure 1. The active area of the membrane electrode assembly is 25 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.

The whole computational domain is a channel (Interdigitated and Serpentine flow fields), 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 (Interdigitated and Serpentine) created in the GAMBIT.

The special add-on module for fuel cell embedded in FLUENT solves the problem considering all the relevant equations of momentum, 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.

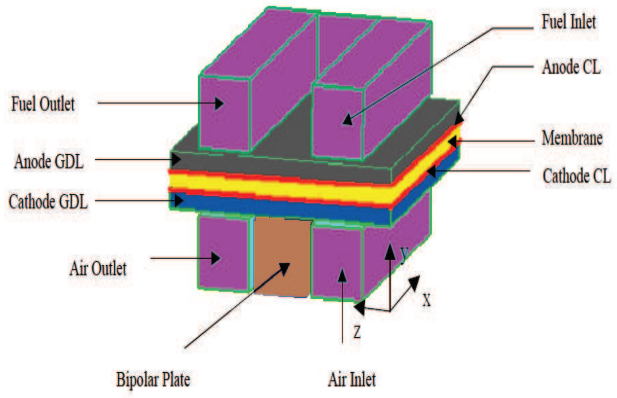

Fig. 1. Three-dimensional computational domain (Components are not to scale)

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 modelling 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 modelling 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 modelling domain comprises all the elements of a complete cell.

4. RESULTS AND DISCUSSION

The values of various geometric details for the three-dimensional CFD model are listed in Table 1. Table 2 shows the electrochemical transport parameters values for base case operating condition as provided by Santarelli and Torchio [1]. The results for base case operating conditions were verified with published experimental results provided by Santarelli and Torchio [1]. The computed polarization curve of PEM fuel cell model is good agreement with the published experimental data is shown in figure 2.

Table 1. Geometrical details for the three dimensional computational domain

Channel length	5mm
Channel width	1.5mm
Rib width	1.8 mm
Channel height	1mm
GDL thickness	0.3mm
Anode catalyst-layer thickness	0.015mm
Cathode catalyst layer thickness	0.015mm
Membrane thickness	0.125mm
Active area	23cm^2

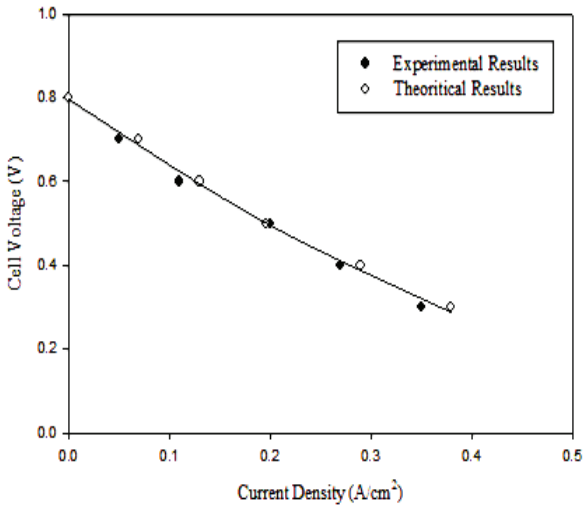

Fig. 2. Comparison of present theoretical results with the experimental data of Santarelli and Torchio [1] (2007) at T=353K, P=1 atm, cathode humidification temperature= 353K, anode humidification temperature = 353 K, H_2 flow rate=0.14 lpm and O_2 flow rate=0.15 lpm

Table 2. Electrochemical transport parameters for base case operating conditions

Terminology	Value	units
Mass flow rate(mo_2)	2.760658 x10^{-7}	Kg/sec
Mass flow rate(mh_2)	1.6103838 x10^{-7}	Kg/sec
Inlet composition at anode (wt.fr.)	H_2 0.1160 H_2O 0.8840	-
Inlet composition at cathode (wt.fr.)	O_2 0.6775 H_2O 0.3225	-
Membrane permeability	1.8x10^{-18}	m^2
Membrane thermal conductivity	0.5	W/mk
GDL thermal conductivity	1.7	W/mk
CL thermal conductivity	0.27	W/mk
GDL and CL permeability	1.76 x10^{-11}	m^2
Membrane electrical conductivity	11.6733	S/m
GDL electrical conductivity	50	S/m
CL electrical conductivity	50	S/m
Membrane density	1980	Kg/m^3
GDL density	400	Kg/m^3
Membrane porosity	0.5	-
GDL porosity	0.5	-
CL porosity	0.5	-
Ref current density at anode	1x 10^9	A/m^3
Ref current density at cathode	1000	A/m^3
H_2 and O_2 ref concentration($C_{H2,ref}$)	0.0408	Kmol/m^3
Anode exchange coefficient	1.0	-
Cathode exchange coefficient	1.0	-
Anode concentration exponent	0.5	-
Cathode concentration exponent	1.0	-
H_2 Diffusivity	1.1 x10^{-4}	m^2/sec
O_2 Diffusivity	3.2 x10^{-5}	m^2/sec

4.1. Effect of cell operating temperature

The temperature has a strong influence in the transport phenomena inside the fuel cell and open circuit voltage. The simulation results are obtained by varying the cell operating temperatures from 323 K to 353 K and kept the constant values of pressure (P= 1 atm), electrode porosity (e = 0.5), relative humidity (RH= 100%), anode flow rate (H_2 gas= 0.14 lpm), cathode flow rate (O_2 gas= 0.15 lpm). The effect of cell operating temperature on cell performance is studied with the flow geometries of interdigitated and serpentine flow fields.

Figure 3 & 4 shows that the performance of the fuel cell increases with increase of the cell operating temperatures from 323 K to 353 K. It can be observed from the figure 3 & 4 that the exchange current density increases with the increase of fuel cell operating temperatures, which reduces the activation losses.

This is due to at low current densities the membrane material in the catalyst layer may not be fully hydrated thus causes a decrease in the active surface area of the catalyst so with the increase of current density, the water production rate increases keep the membrane material in the catalyst layer better hydrated, which causes the increase of active surface area of the catalyst layer and leads to improvement of the fuel cell performance. The polarization power curves for interdigitated and serpentine flow fields are shown in figures 3 & 4.

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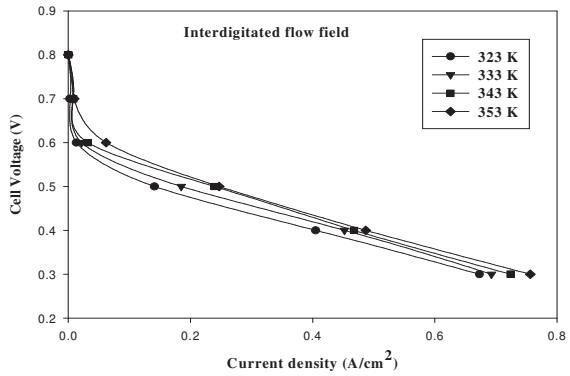

Fig. 3. Effect of cell operating temperature on cell performance in interdigitated flow field at P=1 atm, RH=100 %, H_2 flow rate=0.14 lpm and O_2 flow rate=0.15 lpm.

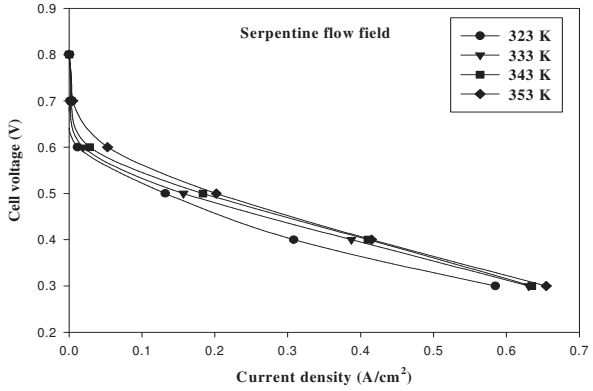

Fig. 4. Effect of cell operating temperature on cell performance in serpentine flow field at P=1 atm, RH=100 %, H_2 flow rate=0.14 lpm and O_2 flow rate=0.15 lpm.

4.2. Effect of cell operating pressure

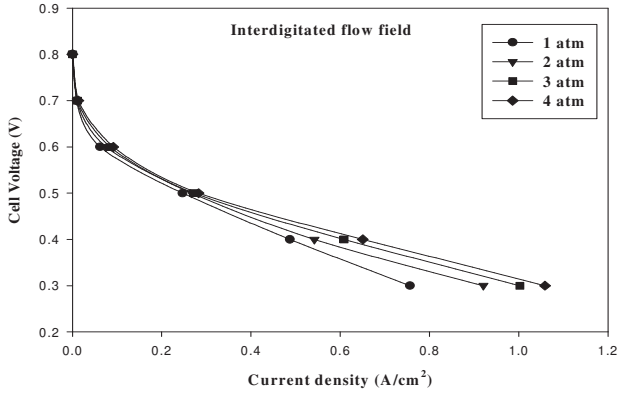

Fig. 5. Effect of cell operating pressure on cell performance in interdigitated flow field at T=353 K, RH= 100%, H_2 flow rate=0.14 lpm and O_2 flow rate=0.15 lpm

Pressure is another effective operating parameter similar to the temperature has a strong influence on the fuel cell performance. The simulation results are obtained by varying the cell operating pressures from 1 atm to 4 atm and kept the constant values of temperature (T= 353 K), electrode porosity (e = 0.5), relative humidity (RH= 100%), anode flow rate (H_2 gas= 0.14 lpm), cathode flow rate (O_2 gas= 0.15 lpm). The effect of cell operating pressure on cell performance is studied with the flow geometries of interdigitated and serpentine flow fields.

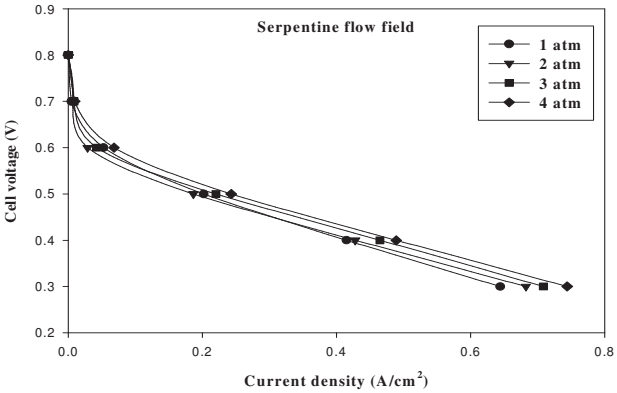

Fig. 6. Effect of cell operating pressure on cell performance (v-i curve) in serpentine flow field at T=353 K, RH=100%, H_2 flow rate=0.14 lpm and O_2 flow rate=0.15 lpm

Figure 5 & 6 shows that the performance of the fuel cell increases with increase of cell operating pressures from 1 atm to 4 atm. It can be observed from the figure 5 & 6 that the exchange current density increases with the increase of cell operating pressures. Since the saturation pressure remains constant for constant operating temperature, the mole fraction of water vapour decreases with increase in total pressure. The mole fraction of oxygen increases with increase in operating pressure. Therefore, higher cell operating pressure results the improvement of fuel cell performance. For the same conditions the polarization curves for interdigitated and serpentine flow fields are shown in figures 5 & 6.

4.3. Effect of relative humidity

Relative humidity (RH) is one of the important operation conditions potentially affecting fuel cell performance. The simulation results are obtained by varying the relative humidity from 25 % to 100 % and kept the constant values of temperature (T= 353 K), pressure (P= 1 atm) electrode porosity (e = 0.5), anode flow rate (H_2 gas= 0.14 lpm), cathode flow rate (O_2 gas= 0.15 lpm). The effect RH on cell performance is studied with the flow geometries of interdigitated and serpentine flow fields.

The effect of RH on the cell performance is shown in figure 7 & 8. From these figures it is observed that the performance of fuel cell increases with increase of RH from 25 % to 100 %. Several factors are responsible for the RH effects including reactant partial pressures, fuel cell reaction thermodynamics and kinetics, mass transfer and membrane conductivity. Mostly, when the fuel cell is operated at high temperatures using a Nafion-115 membrane as an electrolyte, a high relative humidity or nearly saturated humidity (RH >80%) is still required in order to obtain practical performance because the conductivity of the membrane depends on its water content. Therefore, the membrane should maintain a minimum level of the moisture content in order to conduct the protons significantly. So it is observed that at higher current densities the cell performs better at higher RH. This is due to fact that the water concentration decreases in low-humidity gas feed, the oxygen molar concentration increase. Furthermore, at low cell voltage and high current density, water production on the cathode side is sufficient to maintain good proton conductivity. For the same conditions the polarization curves for the interdigitated and serpentine flow fields are shown in figures 7 & 8.

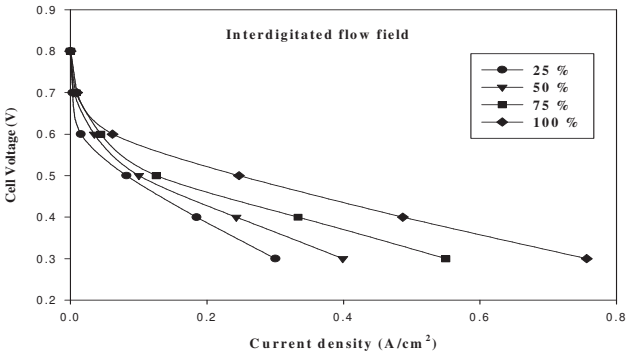

Fig. 7. Effect of relative humidity on cell performance in interdigitated flow field at T=353 K, P=1 atm, H_2 flow rate=0.14 lpm and O_2 flow rate=0.15 lpm

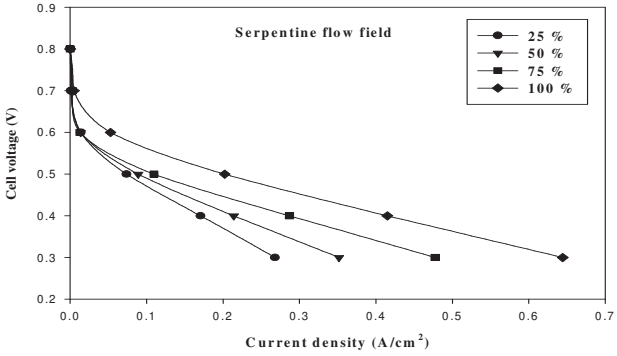

Fig. 8. Effect of relative humidity on cell performance in serpentine flow field at T=353 K, P=1 atm, H_2 flow rate=0.14 lpm and O_2 flow rate=0.15 lpm

4.4. Effect of anode humidification temperature

In order to study the humidification effect, the results are obtained for the same system by varying the anode humidification temperature of the inlet gas from 323 K to 353 K % and kept the constant values of temperature (T= 353 K), pressure (P= 1 atm) electrode porosity (e = 0.5), cathode humidification temperature (T_c= 353 K), anode flow rate (H_2 gas= 0.14 lpm), cathode flow rate (O_2 gas= 0.15 lpm). The effect anode humidification temperature on cell performance is studied with the flow geometries of interdigitated and serpentine flow fields.

The polarization curves at different anode humidification temperatures for interdigitated and serpentine flow fields are shown in figures 9 & 10. The cell performance improves with increase of the anode humidification temperature from 323 K to 353 K. From these figures, it is observed that membrane is not fully hydrated even when the anode humidification temperature equals to the cell temperature. This improvement of the cell performance may be caused by the enhancement of water transport within the flow fields.

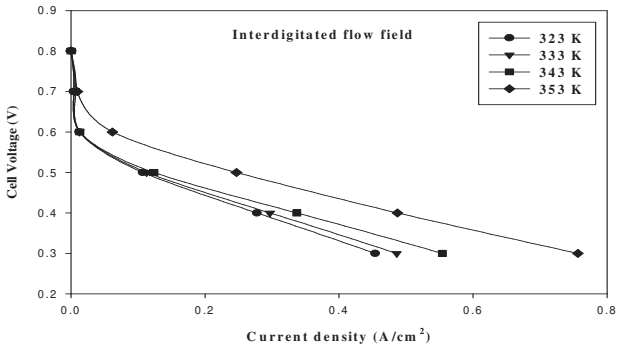

Fig. 9. Effect of anode humidification temperature on cell performance in interdigitated flow field at T=353K, P=1 atm, RH=100%,cathode humidification temperature= 353K, H_2 flow rate=0.14 lpm and O_2 flow rate=0.15 lpm

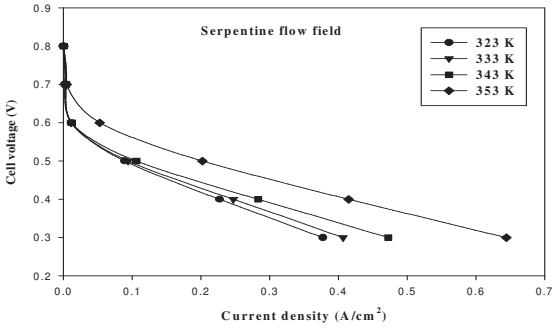

Fig. 10. Effect of anode humidification temperature on cell performance in serpentine flow field at T=353K, P=1 atm, RH=100%, cathode humidification temperature= 353K, H_2 flow rate=0.14 lpm and O_2 flow rate=0.15 lpm

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4.5. Effect of cathode humidification temperature

In order to study the humidification effect, the results are obtained for the same system by varying the cathode humidification temperature of the inlet gas from 323 K to 353 K % and kept the constant values of temperature (T= 353 K), pressure (P= 1 atm) electrode porosity (e = 0.5), anode humidification temperature (T_a= 353 K), anode flow rate (H_2 gas= 0.14 lpm), cathode flow rate (O_2 gas= 0.15 lpm). The effect cathode humidification temperature on cell performance is studied with the flow geometries of interdigitated and serpentine flow fields.

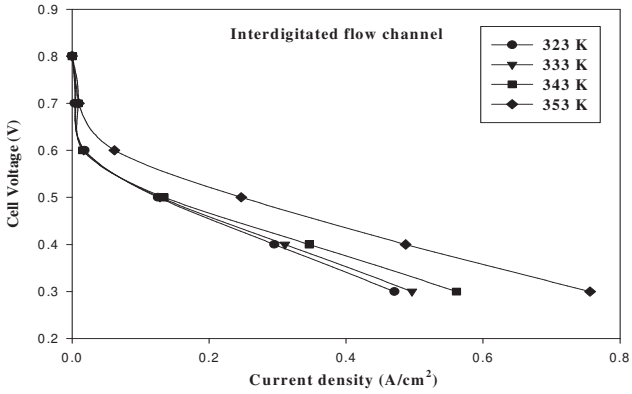

Fig. 11. Effect of cathode humidification temperature on cell performance in interdigitated flow field at T=353K, P=1 atm, RH=100%, anode humidification temperature= 353K, H_2 flow rate=0.14 lpm and O_2 flow rate=0.15 lpm

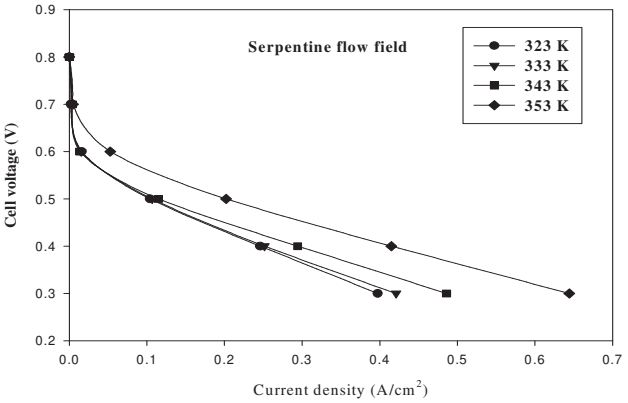

Fig. 12. Effect of cathode humidification temperature on cell performance in serpentine flow field at T=353K, P=1 atm, RH=100%, anode humidification temperature= 353K, H_2 flow rate=0.14 lpm and O_2 flow rate=0.15 lpm

The polarization curves at different cathode humidification temperatures for interdigitated and serpentine flow fields are shown in figure 11 & 12. The cell performance improves with increase of the cathode humidification temperature from 323 K to 353 K. By comparing Figure 9 with Figure 11 for interdigitated flow field, it shows clearly that when the anode humidification temperature is higher than the cell temperature, the cell performances are better than that with the higher cathode humidification temperature than the cell temperature. The results indicate that no matter how much humidification is provided to the cathode side, if the anode humidification is not enough, the portion of the membrane close to the anode will not be fully hydrated. This is caused by water transfer from the anode to cathode side due to electro-osmosis.

4.6. Effect of flow field designs

Effect of flow field designs play an important role on the cell performance of PEMFC. The theoretical results obtained for two different flow fields namely, serpentine and interdigitated at a cell operating temperature 353K, cell operating pressure 1 atm, relative humidity 100 %, anode flow rate 0.14 lpm, and cathode flow rate 0.15 lpm. From the figure 13, it is observed that the interdigitated flow field gives the better cell performance than in serpentine flow field. This is due to the presence of dead ends (Availability of gas concentrations is more at the respective sides), the active transport of reactants in close vicinity to the electrode. Therefore, the diffusion of gas is more in interdigitated flow field than serpentine flow field.

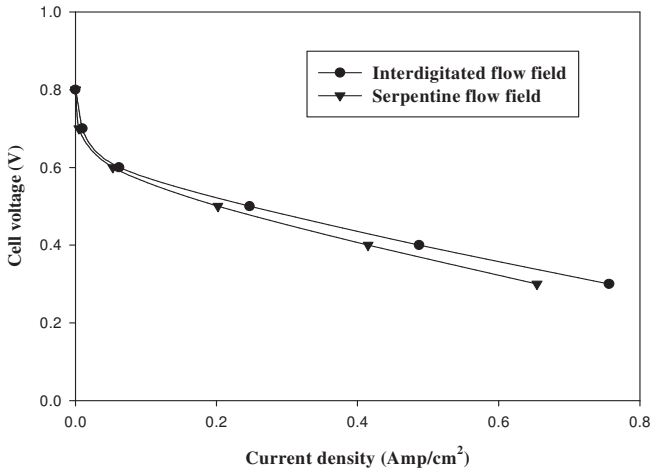

Fig. 13. Effect of flow field designs on cell performance at T=353K, P=1 atm, RH= 100%, H_2 flow rate=0.14 lpm, O_2 flow rate= 0.15 lpm

5. CONCLUSIONS

A theoretical analysis is carried out for a 3-D computational PEM fuel cell model in FLUENT software and to study the effects of various operating parameters on the cell performance for serpentine and interdigitated flow field. Based on this study, the following conclusions can be made.

- The theoretical model developed for single PEM fuel cell simulates effectively the various conditions that exit in a real fuel cell, which is evident from the comparison of the theoretical results with experimental data.
- The fuel cell performance is enhanced as the cell operating temperature goes up from 323 K to 353 K. This is due to increase of membrane conductivity, gas diffusivity and the exchange current density at higher temperatures.
- The performance of the fuel cell increases with the increase in operation pressure from 1 atm to 4 atm due to the increase of the exchange current density and the reactant gas partial pressures.
- The performance of fuel cell is improved with the increase of relative humidity from 25 % to 100%. This is due to the conductivity of the membrane (maintain a minimum level of moisture content).
- The fuel cell performance is improved with the increase of both anode and cathode humidification temperatures from 323 K to 353 K due to the effective water transport within the flow field.
- At the same operating conditions and reactant relative humidities, the interdigitated flow field design has better cell performance than the serpentine flow field design. This is due to the presence of dead ends (Availability of gas concentrations is more at the respective sides), the active transport of reactants in close vicinity to the electrode which enhances liquid water removal.

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