Flow Field Orientation Effect on Performance of a Proton Exchange Membrane Fuel Cell using Nanocatalyst Support

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Abstract
Orientation of flow channels and relative positions of cathode and anode outlet manifolds are vital due to gravity effect on water that condenses inside a proton exchange membrane fuel cell (PEMFC). Anode and cathode manifolds may be oriented in co-flow (same direction), counter-flow (opposite direction) or in cross-flow (perpendicular) configurations. Flow field orientation allows water exchange through the membrane due to concentration gradient. It has a good effect on liquid water removal upon shutdown of the PEMFC. Hence flow orientation can be considered as a crucial parameter in the design of PEMFC with efficient water removal. In the present work, a membrane electrode assembly (MEA) was fabricated using Nafion® 212 membrane and electrodes were prepared using equal loadings (0.4mg/cm^2 on anode and 0.4mg/cm^2 on cathode) of 20% Pt/MWCNT nanocatalyst, which was synthesized in-house. The fabricated MEA was tested in a single PEMFC assembly using graphite plates with serpentine-parallel geometry having 25 flow channels. Pure H$_2$and O$_2$ was used as the fuel and oxidant respectively. Different orientations of the flow field plates, i.e., co-flow,counter-flow and cross-flow were used to study cell performance under the influence of variable operating parameters such as cell temperature and gas humidification temperatures. Results were presented in the form of polarization and power curves, which were analyzed to find the optimum flow channel orientation that delivers maximum performance while displaying enhanced water removal characteristics.

Keywords*: PEM fuel cell, flow field orientation, serpentine-parallel, water management, membrane electrode assembly.*

INTRODUCTION

Fuel cells have attracted much interest over the past few decades. The exigency for a clean and efficient alternate solution to the internal-combustion engine fueled by the ongoing energy crisis has led to worldwide focus on fuel cells. Fuel cells are considered as the most suitable for terrestrial and transportation applications due to their high efficiency and zero emission. Consequently, fuel cell powered electric vehicles are being adopted by majority of the automobile manufacturers to either supplement or replace battery powered electric vehicles. Hydrogen has gained popularity as the fuel in fuel cell powered electric vehicles due to its high conversion efficiency, zero emission and also since it produces water as the end product. Fuel cells can also be designed for low temperature and high CO$_2$ tolerance in addition to better output efficiency.

Jung-Ho We [1] discussed the challenges and recent advances in application test of PEMFC to transportation, residential power generation and portable computers. Y Wang et al. [2] reviewed the status of PEMFC technology development and applications in the transportation, stationary, and portable power generation sectors. B Sreenivasulu et al. [3] studied

the effects of various operating parameters on the output of a PEMFC using 4-serpentine flow channel by simulating the problem using Fluent. Sk. Shadulla and S V Naidu [4] developed a 3-D computational model for PEMFC with an active area of $25cm^2$. The developed model was validated with published results from literature.

H Liu et al. [5] ran experimental tests to study the effect of flow channels on PEMFC performance. Graphite plates with different flow field designs taken from literature and some novel flow channel designs were used in the PEMFC assembly. S Kreesaeng et al. [6] found the impact of cathode flow field design with variable cross-sectional area and aspect ratio on the performance of a PEMFC. N J Cooper et al. [7] examined experimentally a wide range of critical cathode bipolar plate channel dimensions such as rib/channel width and channel depth and their impact on cell performance at various conditions.

S H El-Emam et al. [8] explored the effect of stack orientation and vibration on PEMFC performance. A single PEMFC fitted with serpentine anode and straight cathode flow designs were used in the experiments. M Ashrafi and M Shams [9] developed a numerical scheme to investigate the impact of flow-field orientation on water management in PEM fuel cell. D G Sanchez et al. [10] found out the influence of inlet gas humidification on cell performance by in-situ current density and measurements obtained using segmented cell approach.

D N Ozen et al. [11] studied the effect of operation conditions on performance of a PEMFC and results were presented together with a comprehensive literature review. Shadulla et al. [12] conducted a series of experimental tests to investigate the impact of various operating parameters such as cell temperature, pressure, gas humidification temperatures and flow rates on PEMFC performance. Results were presented in the form of polarization and power curves which demonstrate the impact of operating parameters on cell performance.

Among the various components of the PEMFC, the flow field plates are considered paramount in affecting cell performance. In the present work, a 20% Pt/MWCNT catalyst was synthesized using a novel technique and a membrane electrode assembly (MEA) was fabricated. Graphite plates of serpentine-parallel configuration were used in the single PEMFC assembly with different orientations. A parametric study was conducted to investigate the impact of flow field orientation under the influence of variable operating parameters such as cell temperature and gas humidification temperatures on cell performance.

Fabrication of Membrane Electrode Assembly (MEA)
Commercially available 99% isopropyl alcohol (IPA), 69% HNO_3, 30% H_2O_2 and 98% H_2SO_4 were procured from Merck India and used without further treatment. Multiwalled carbon nanotubes (MWCNTs) were procured from D & D Advanced Materials, Pune with OD 10 – 15 nm and length 1.13 – 1.53 µm. 5% Nafion® solution, Nafion® 212 membrane, Chloroplatinic acid and Hydrazine Hydrate were procured from Johnson Matthey. Gas diffusion layer (GDL) of Ballard-make was procured from Sainergy Fuel Cell India. De-ionized (DI) water was used in the synthesis process.

Nafion® 212 membrane was pre-treated using HNO_3, H_2O_2 and H_2SO_4 to remove

organic and metallic impurities and regenerate proton conductivity. Membrane was also thoroughly treated with DI-water prior to MEA preparation. The treated membrane was sandwiched between the prepared electrodes (anode and cathode) and thermally pressed together to form the membrane electrode assembly (MEA). Thermal pressing was achieved using a 15-ton hydraulic hot press.

Fuel Cell Setup and Polarization Measurements

Experimental tests were performed using a 250W Biologic FCT-150S PEM fuel cell test station which can control and measure the output current, voltage and power as shown in figure 1 below. Pure hydrogen, oxygen and nitrogen were used with fixed stoichiometry. The PEM fuel cell was operated at 0.6 V until steady-state was achieved. After steady-state conditions prevailed, the V-I data was logged by changing the voltage values from 0.3 V to 0.7 V.

Fig: 1. Biologic FCT 150S PEM fuel cell setup

Experimental Analysis of Cell Performance with Different Flow Field Orientations:

Graphite plates of serpentine-parallel configuration having 25 parallel paths with intermittent serpentine turns were used as the anode and cathode flow field plates. An illustration of the different flow configurations examined is depicted below. Pure H_2 was used as the fuel and pure O_2 was used as the oxidant while pure N_2 was used as the purge gas. Gas flow rates were fixed at 0.25 lpm for hydrogen and 0.50 lpm for oxygen throughout the study.
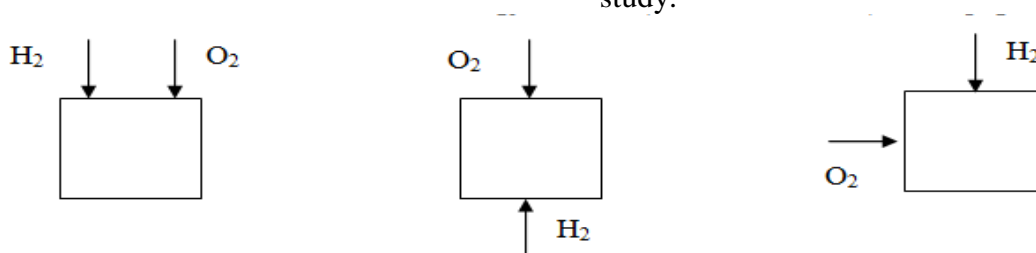
(1) Co-flow orientation   (2) Counter-flow orientation   (3) Cross-flow orientation

In co-flow orientation, hydrogen and oxygen were fed from the top inlet of the fuel cell and exit from the bottom manifold on the anode side and cathode side respectively. This configuration allows for better water removal as water that condenses in the PEMFC exits from the bottom outlet due to gravity effect. In counter-flow orientation, hydrogen was fed from the bottom inlet at the anode side while oxygen was fed from the top inlet at the cathode side of the fuel cell. This configuration ensures maximum fuel utilization as hydrogen, being a lighter gas, traverses a longer path in the upward direction through the 25 serpentine-parallel flow channels. Water removal is also enhanced due to gravity effect on condensed water in the PEMFC due to downward flow of oxidant. In cross-flow orientation, hydrogen was fed from the top inlet at the anode side while oxygen was

fed from the side inlet at the cathode side of the fuel cell.

Table 1 shows the range of operating parameters examined in this study. The PEMFC assembly was operated under constant voltage mode where in current densities were logged at operating voltages ranging from 0.3 V to 0.7 V.

Table 1: Range of operating parameters examined

S. No	Parameter	Range	Units
1	Cell temperature	30 – 50	^{o}C
2	Anode humidification temperature	30 – 60	^{o}C
3	Cathode humidification temperature	30 – 60	^{o}C

Effect of Cell Temperature

Experimental analysis of MEA performance was carried out at cell temperatures ranging from 30 ^{o}C to 50 ^{o}C while the gas humidification temperatures were held constant at 30 ^{o}C. An increase in cell temperature results in improved reaction kinetics in the electrode catalyst layer. This in turn reduces activation losses due to increased exchange current density and gas diffusivity, thus contributing to improved fuel cell performance. Polarization curves demonstrating the cell temperature effect are shown in figures 2, 3 and 4 for co-flow, counter-flow and cross-flow orientations. The polarization curves show improved fuel cell performance in the lower as well as higher current density regions. When cell temperature exceeds humidification temperature, partial membrane hydration in catalyst layer results in a reduction in active surface area of the catalyst at low current densities. But at higher current densities, better water production rate compensates the membrane hydration resulting in improved fuel cell performance.
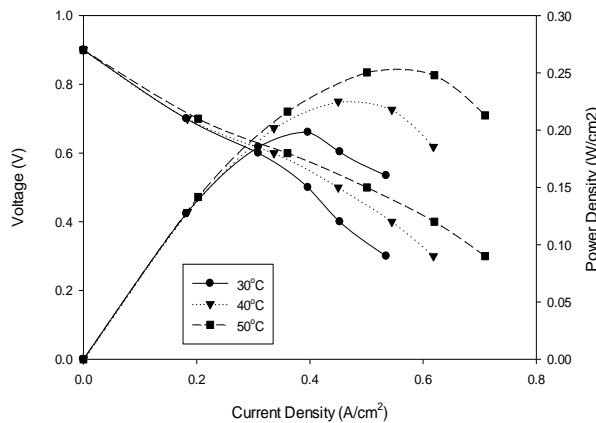

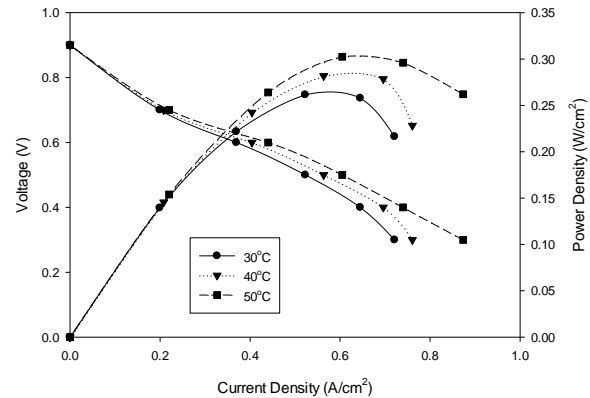*Fig: 2. Polarization and Power curves showing cell temperature effect for co-flow at humidification temperatures of 30 ^{o}C.*

Fig: 3. Polarization and Power curves showing cell temperature effect for counter-flow at humidification temperatures of 30 ^{o}C.
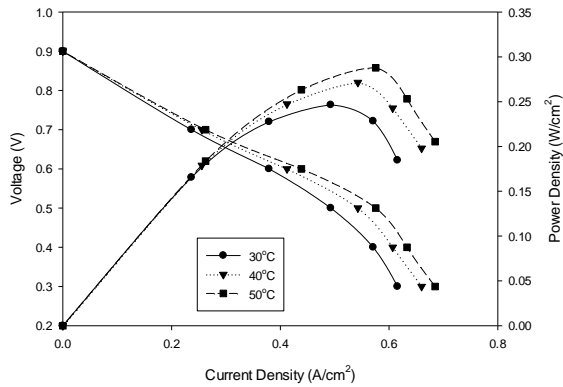
Fig: 4. *Polarization and Power curves showing cell temperature effect for cross-flow orientation at gas humidification temperatures of 30 °C.*

At a reference voltage of 0.6V, the following values were obtained at cell temperature of 50°C:

Orientation	Current Density	Power Density
Co-flow	0.3604A/cm^2	0.2162 W/cm^2
Counter-flow	0.4400 A/cm^2	0.2640 W/cm^2
Cross-flow	0.4388 A/cm^2	0.2633 W/cm^2

Effect of Anode Gas Humidification Temperature

Anode humidification temperature effect was examined by varying its value from 30 °C to 60 °C while the cell and cathode gas humidification temperatures were held constant at 50 °C and 30 °C respectively. Polarization curves demonstrating the anode gas humidification temperature effect is shown in figures 5, 6 and 7 for co-flow, counter-flow and cross-flow orientations. When anode humidification temperature is at 30 °C, the current density of the fuel cell is at its lowest. At lower anode humidification temperatures, partial membrane hydration in the catalyst layer results in reduced active surface area of the catalyst at low current densities. Membrane hydration at anode side is caused by predominant back-diffusion of water due to electro-osmotic concentration gradient. This leads to dehydration of membrane at the cathode side. At higher
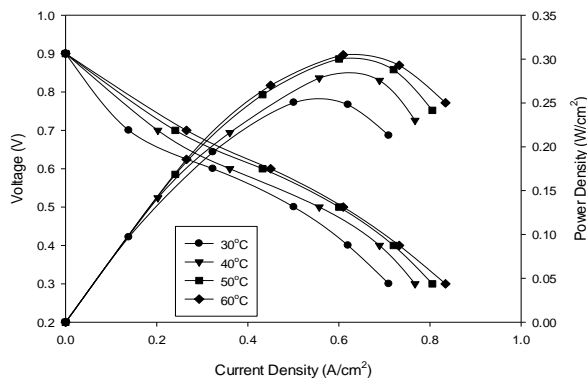

Fig: 5. *Polarization and Power curves showing anode temperature effect for co-flow at cell temperature of 50 °C, cathode gas humidification temperature of 30 °C.*
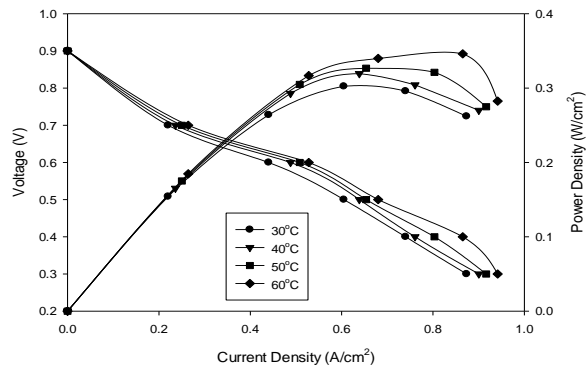

Fig: 6. *Polarization and Power curves showing anode temperature effect for counter-flow at cell temperature of 50 °C, cathode gas humidification temperature of 30 °C.*
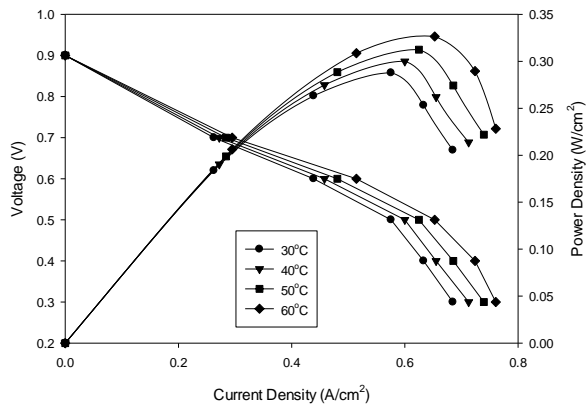
Fig: 7. Polarization and Power curves showing anode temperature effect for cross-flow orientation at cell temperature of 50 ^{o}C, cathode gas humidification temperature of 30 ^{o}C.

At a reference voltage of 0.6V, the following values were obtained at cell temperature of 50 ^{o}C, anode humidification temperature of 60 ^{o}C and cathode humidification temperature of 30 ^{o}C:

Orientation	Current Density	Power Density
Co-flow	0.4500 A/cm^2	0.2700 W/cm^2
Counter-flow	0.5280 A/cm^2	0.3168 W/cm^2
Cross-flow	0.5144 A/cm^2	0.3086 W/cm^2

current densities, it is observed that cell voltages at different anode humidification temperatures start overlapping. At higher current densities, water generation rate also increases and water transfer due to electro-osmosis from cathode to anode is high, resulting in better membrane hydration on both sides.
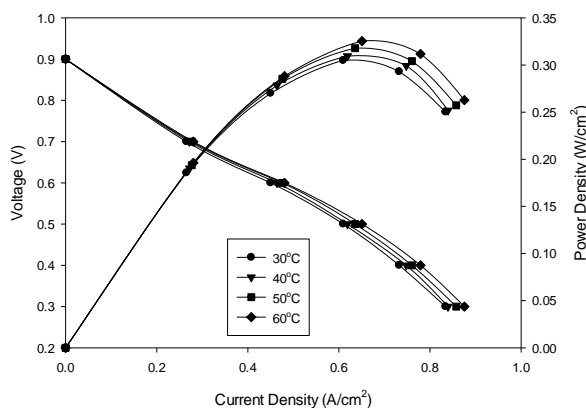
Effect of Cathode Gas Humidification Temperature

Experiments were conducted by varying the cathode humidification temperature from 30 ^{o}C to 60 ^{o}C while the cell and anode gas humidification temperatures were held constant at 50 ^{o}C and 60 ^{o}C. When cathode gas humidification temperature is varied from 30 ^{o}C to 60 ^{o}C, there is no apparent change in performance as is evident from figure 8, 9 and 10 for co-flow, counter-flow and cross-flow

Fig: 8. Polarization and Power curves showing cathode temperature effect for co-flow at cell temperature of 50 ^{o}C, anode gas humidification temperature of 60 ^{o}C.
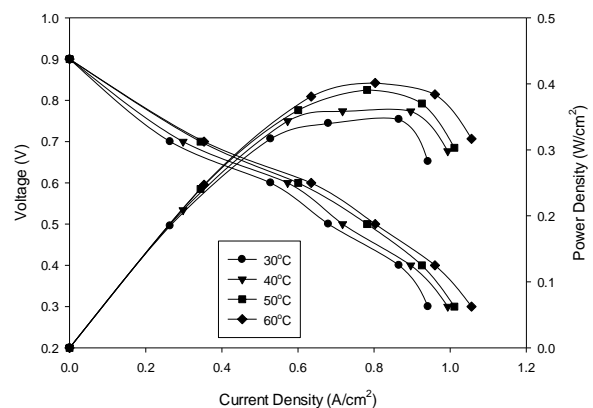

Fig: 9. Polarization and Power curves showing cathode temperature effect for counter-flow at cell temperature of 50 ^{o}C, anode gas humidification temperature of 60 ^{o}C.
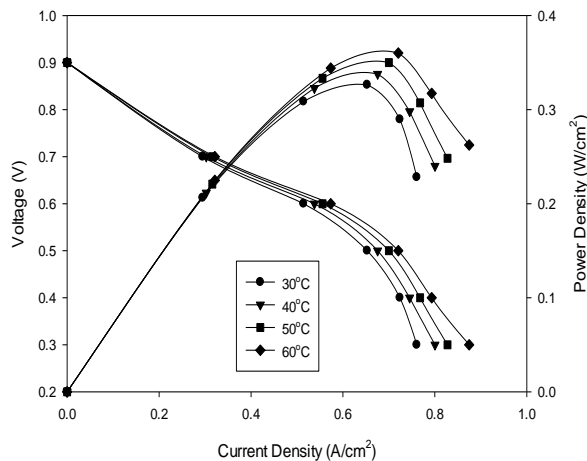
Fig: 10. Polarization and Power curves showing cathode temperature effect for cross-flow orientation at cell temperature of 50 ^{o}C, anode gas humidification temperature of 60 ^{o}C.

At a reference voltage of 0.6 V, the following values were obtained at cell temperature of 50 ^{o}C, anode humidification temperature of 60 ^{o}C and cathode humidification temperature of 60 ^{o}C:

Orientation	Current Density	Power Density
Co-flow	0.4804 A/cm^2	0.2882 W/cm^2
Counter-flow	0.6348 A/cm^2	0.3809 W/cm^2
Cross-flow	0.5736 A/cm^2	0.3442 W/cm^2

orientations. As cathode humidification temperature increases, more water starts accumulating at the cathode side which is complemented by water generation due to proton exchange. The concentration gradient drives back-diffusion of water from the cathode to the anode. We can only observe the decreasing trend of the limiting current density with an increase in cathode humidification temperature. This occurrence is due to a decrease of the effective porosity of the gas diffusion layers and a decrease of reactant concentration.

Effect of Flow Field Orientation:
Comparative polarization curves for co-flow, counter-flow and cross-flow orientations of the PEMFC assembly at a cell temperature of 50 ^{o}C, anode and cathode gas humidification temperatures of 60 ^{o}C respectively are as shown in figure 11. From the polarization curves, it is evident that counter-flow orientation demonstrates better cell performance when compared to co-flow and cross-flow orientations under similar conditions. In counter-flow orientation, the flow of hydrogen in the upward direction ensures maximum fuel utilization as hydrogen takes a longer time to traverse the entire 25 serpentine-parallel path. Consequently, the output current density is higher at given conditions as compared to co-flow and counter-flow orientations. A current density of 0.6348 A/cm^2 and a power density of 0.3809 W/cm^2 was obtained for counter-flow configuration at reference voltage of 0.6 V.
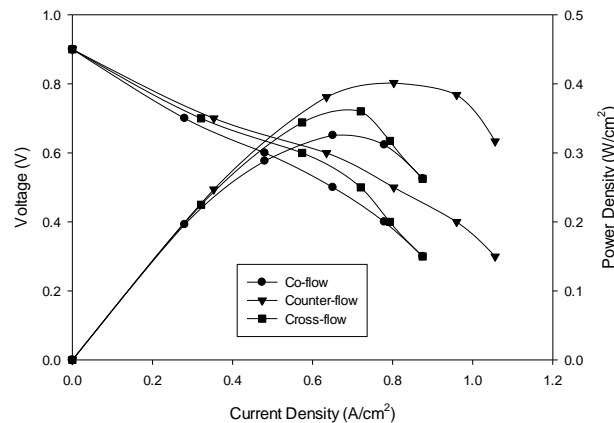
Fig: 11. Polarization and Power curves showing effect of flow field orientation for cell temperature of 50 °C and gas humidification temperatures of 60 °C each.

CONCLUSIONS

Experimental analysis was conducted for a single proton exchange membrane fuel cell of 25 cm² active area assembled with an in-house fabricated MEA and fed with pure H_2 and pure O_2 as the fuel and oxidant. The objective was to investigate the impact of flow field orientation under the influence of variable operating parameters such as cell temperature and gas humidification temperatures on PEMFC performance. Based on experimental observations, the following conclusions were made:

1. With an increase in operating temperature from 30 °C to 50 °C, better PEM fuel cell performance was observed due to an increase in membrane hydration, gas diffusivity and exchange current density.

2. Gas humidification temperatures have considerable impact on PEM fuel cell performance. When the anode gas humidification temperature is increased from 30 °C to 60 °C, the cell performance is enhanced due to increased membrane conductivity and decreased ohmic loss. When the anode gas humidification temperature exceeds the cell operating temperature, cell performance improvement becomes visible at low current densities.

3. Changes in cathode gas humidification temperatures have no significant impact on PEM fuel cell performance. Only the decreasing trend of the limiting current density with an increase of cathode gas humidification temperature can be observed.

4. Comparative polarization curves for all three flow field orientations at cell temperature of 50 °C and gas humidification temperatures of 60 °C shows that counter-flow orientation demonstrates best PEMFC performance along with enhanced water removal characteristics.

ACKNOWLEDGEMENTS

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