Int. J. Electrochem. Sci., 13 **(2018)** 10480 – 10495, doi: 10.20964/2018.11.22

International Journal of
ELECTROCHEMICAL
SCIENCE
www.electrochemsci.org

Review

Effects of Gas Channel Design on Water Management and on the Performance of Polymer Electrolyte Membrane Fuel Cells: A Review

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Received: 14 June 2018 / *Accepted:* 18 July 2018 / *Published:* 1 October 2018

Recently, polymer electrolyte membrane fuel cells (PEMFCs) have been studied by scientists worldwide as tools that can replace traditional energy sources to address issues related to energy depletion and environmental pollution. PEMFCs present many advantages for various applications, such as their high efficiency, ability to self-start at low temperatures and clean emissions. However, PEMFCs have not yet been widely used in applications due to their high manufacturing costs and low levels of power density. Flow-field design optimization serves as a good means to enhance fuel cell operations; as a result, many studies have focused on optimizing the flow field to improve water management and fuel cell performance output. The paper provides a review of a variety of studies conducted on flow-field configuration design that contribute greatly to water management and fuel cell operation. Regarding pin-type flow fields, the design uses several pins of various shapes arranged in a rectangular or spherical configuration. The membrane can become dry as a result of over water discharge. Meanwhile, for straight and parallel configurations, such designs include many separate parallel flow channels that connect the inlet to the outlet. These designs are simple and require the lowest level of pressure drop by equally distributing gases into parallel paths. Some works have designed bipolar plate configurations that include multi-pass serpentine flow fields, which enhance under-rib convection, generate a more uniform gas distribution, and quickly remove water from under-rib regions. A geometrical characterization shows that multi-pass serpentine flow fields strengthen under-rib convection intensities and support more uniform conditions in terms of gas concentrations, temperatures, and pressure levels in comparison to conventional serpentine flow fields.

Keywords: Polymer electrolyte membrane fuel cell; Flow-field design; Under-rib convection; Diffusion, Water management; Polarization performance

1. INTRODUCTION

Recently, problems related to energy depletion and environmental pollution have presented great challenges that have motivated humans to find renewable energy sources to achieve sustainable development. As described in many works [1-3], vehicles using fossil fuels are widely recognized to be a major source of environmental pollution globally. The majority of vehicle emissions include carbon dioxide (CO_2) and water generated from the complete combustion of fuel. However, the combustion process is typically incomplete in real conditions, as a small fraction of the fuel is oxidized to carbon monoxide (CO). Furthermore, some unburned hydrocarbons (HC) and carbonaceous particles generated from incompletely burnt fuel droplets (PM) are also emitted in exhaust. In addition, nitrogen oxide (NOx) can form at high combustion temperatures.

Fuel cells have been known to science for more than 100 years. The first fuel cell was invented by William Robert Grove in 1839. Grove performed a series of experiments that ultimately showed that an electric current can be created from the reaction of hydrogen and oxygen over a platinum catalyst. However, the materials that Grove used were unstable; as a result, his approach was not popular until the 1960s when fuel cells were developed for use on manned space vessels built by NASA. Fuel cells can run on various types of fuels such as hydrogen, alcohol, coal gas, and even coal powder. When using other hydrocarbons as fuel, a reformer can produce small volumes of pollutants but at much lower levels than those generated from traditional combustion generators. Fuel cells have been commercially used in various applications since 2007 when some supplier companies sold to consumers with written warranties and service capabilities. In particular, a large variety of PEMFC and direct methanol fuel cell auxiliary power units have been applied to leisure applications, with a similar number of micro fuel cell units sold as toys and for educational applications.

Fuel cells emit fewer exhaust emissions and are more efficient than other traditional power sources, as fuel chemical energy is directly converted into electricity without combustion [4-5]. However, as noted in many studies, fuel cells suffer from low levels of power density [5-6]. With the same characteristics of membrane electrode assemblies (MEA), fuel cell power can be significantly enhanced by strengthening the mass transfer phenomenon. This can be defined as mass transfer occurring between electrodes and the flow field through diffusion and convection. Therefore, the design of a flow-field configuration is important due to effects of the shape and dimension of the flow field on fuel cell operation [5, 7].

Many scientists have performed studies to improve fuel cell performance by optimizing the flow-field configuration. However, such work is very complicated due to the complex mass transport phenomena of fuel cell operations. The most difficult issue related to flow-field design concerns the prediction of gas-liquid two-phase flow development within channels [8]. As presented in [9], a review of this flow development has been performed through experimentation and simulation. The review focuses on the gas-liquid two-phase flow of mini- and micro-channels related to PEMFC operations. In situ and ex situ experimental setups have also been utilized to visualize and quantify two-phase flow phenomena from flow regime maps and pressure drop measurements [9]. Water management strategies are critical to enhancing fuel cell operation, as while water enhances membrane ionic conductivity, excess liquid water spurs water flooding in gas diffusion layer (GDL) and channel clogging [5–6].

Given low operating temperatures maintained during start up and hence low-saturation pressures, two-phase phenomena are unavoidable during fuel cell operation [10]. Two-phase transport occurring through a fuel cell involves three sub-problems: catalyst layer flooding, GDL flooding, and two-phase flows through channels [10-11]. Recently, most related efforts have focused on two-phase modelling while few models of channel flooding have been developed [10–14]. On a related note, a three-dimensional simulation based on a single domain approach to reactants and products of a fuel cell with straight flow field channels has been conducted [15]. The results of this study show that water vapour is mainly concentrated in the GDL underneath the bipolar plate as a result of deceleration resulting from collector contraction impact, but this still occurs far from the catalyst layer. This result highlights the important role of the porous media of GDL, which prevents severe levels of liquid flooding from occurring on the cathode side. In another study Alfredo Iranzo et al. [8] illustrated an experimental procedure for investigating water liquid accumulation occurring in the channels of a serpentine flow field by using neutron imaging to observe the distribution of liquid water corresponding to various operating conditions. The results of this study illustrate major effects of the gas flow direction on water accumulation within channels with dramatically more water liquid accumulating in channels with upwards gas flows. Meanwhile, in [16] computational fluid dynamics techniques are investigated to optimize PEMFC configuration. The authors built 3D numerical models using commercial simulation software to simulate fuel cell simulations. The results show that gas flow distributor permeability plays an important role in the consumption of reactant gas in electrodes. In addition, porous materials are superior to grooved plates in terms of reactant gas utilization [16].

As is shown by many previous studies, high convection phenomena help improve fuel cell performance, as they not only support the transfer of reactants from channels to porous GDLs and catalyst layers but also contribute to the removal of formed liquid water from cells [17-24]. To enhance GDL convection, previous studies [17-21] have examined performance flow-field designs including multi-pass serpentine configurations; such designs enhance under-rib convection, generate more uniform gases, and facilitate rapid water removal from under-rib regions. J.H. Nam et al. [24] increased the path-length difference of serpentine flow fields based on their hypothesis. They showed that the resulting maximum path-length difference observed between adjacent channels enhances under-rib convection and thereby improves PEMFC performance.

The aim of this work is to provide a review of the effects of flow-field design on water management and fuel cell operation. Consequently, various configurations of flow fields are examined to determine the best flow-field design that enhances fuel cell performance. A number of fuel cell characteristics corresponding to flow-field designs (e.g., liquid water removal; uniformity of concentrations, pressure levels, temperature and current density distributions; and power density) are empirically examined using experimental and numerical studies. This work is intended to illustrate the foundations of flow-field design based on the promotional role of under-rib convection; the optimization process applies state-of-the-art designs that are likely to change as this mode of technology continues to develop.

2. FUEL CELL OPERATION

A single fuel cell includes the following main components: an anode and cathode bipolar plate, an anode and cathode GDL, an anode and cathode catalyst layer, and a membrane. In the operation of PEMFCs, heat and water are generated from electrochemical reactions occurring between hydrogen and oxygen, which generates electricity [25-34]. The principal operation of a PEMFC is as follows: the catalyst oxidizes hydrogen gas into positively charged ions and into a negatively charged electron on the anode side, and protons can pass through electrolyte while electrons cannot due to the design of the membrane [33-37]. In addition, free electrons travel from the anode to the cathode side across a wire to generate electricity. Meanwhile, oxygen moves across the cathode gas diffusion layer through pressure-driven convection and concentration-driven diffusion passing through the porous GDL [31-41]. Water vapour in the gas-flow channel of the cathode can become saturated, as the operation temperature of PEMFCs is below the boiling point of water, and additional water produced at the cathode must be immediately condensed. When oxygen is consumed at cathode catalyst layers, there is a decrease in oxygen pressure resulting from a reduction in the total number of moles in the vapour. The fuel cell centre is the MEA, which is normally positioned between two flow field plates that are often mirrored to form a bipolar plate when cells are stacked as a series to generate higher voltages. The MEA includes a polymer electrolyte membrane, catalyst layers, and gas diffusion layers [42-43]. These components are typically individually fabricated and then pressed together at high temperatures, at high pressure levels and under other conditions as clearly given in [24].

3. IMPACTS OF FLOW-FIELD DESIGN ON FUEL CELL OPERATION

3.1. Structured Approaches to Flow-Field Optimization

Fuel cell performance is normally determined from the intrinsic electrochemical efficiency of the MEA [6]. In addition, other factors including flow-field design water management strategies and levels of operating boundary control are also important [44]. The flow field is a key component of a PEMFC and serves as both a current collector and reactant distributor [6, 45-48]. Reactants and products are transferred to and from the cell through flow channels. Essential requirements are uniform reactants throughout the entire surface area, which effectively move formed water from the cell to limit concentration polarization. Normally, flow plates contain either a few very long channels or varying channels. These channels make up the flow to move reactants across the entire surface of the MEA. An optimal flow-field design is critical for generating high levels of power density within a fuel cell and thus is extremely important. The operation of PEMFC within a narrow band of water content is a challenging task given power requirements and environmental conditions of vehicular applications [6]. Under different flow rates, the relative humidity of air intake and different current requirements, complex two-phase flow regimes have been observed in channels [6]. Consequently, it is necessary to design blockage-resistant gas channels to limit pump hydrogen and oxygen power loss. Data have been drawn from studies conducted on flow field optimization applying both experimental [49-66] and modelling approaches [67–76].

3.2. Impacts of flow-field patterns on fuel cell operation

During operation, PEMFC mass transfer can be defined as the mass transport of electrodes and of the flow field resulting from diffusion and convection phenomena. These processes are affected flow-field transformations, as mass transfer optimization can limit concentration loss. Flow-field configuration design is an important factor due to effects of the shape, size, and patterning of corresponding flow fields on fuel cell performance. Effects of flow-field configurations on channel dimensions and results relating to current density, temperature and membrane water content distributions have been studied [77-96]. Electrochemical variables fitted by polarization curves of experiment have been used to examine the impacts of design parameters on PEMFC operations [1, 23]. In pin-type designs, the flow-field network includes several pins of various shapes constructed in a regular or sphere configuration [1, 95-97]. In this design, dry membrane phenomena can occur as a result of excessive water discharge [98]. For straight and parallel designs, configurations include multi-parallel flow channels that guide gases from the inlet to the outlet.

As noted above, the flow-field design of a fuel cell is very difficult as mass transport and electrochemical reactions are difficult to define and cannot be separately measured. The mass transfer behaviours of hydrogen and oxygen gases and of formed water in channels and under the ribs of flow fields are hardly observable empirically; consequently, simulation is critical to design in finding suitably efficient flow fields for PEMFC operation. As noted in [99], fuel cell operation has been numerically performed with four different flow-field designs of single serpentine flow field patterns (SSFFPs), single parallel flow field patterns (SPFFPs), interdigitated flow-field patterns (IFFPs) and pin flow-field patterns (PFFPs). Calculations executed were based on with steady-state three-dimensional CFD models applying the same boundary conditions given in [99]. Assumptions used in these calculations are as follows: the model is of a steady state, includes ideal gas properties, and involves homogeneous two-phase flows [99].

Liquid water relates directly to membrane water content as noted in many previous works [5-6, 100-102]. Average membrane water content and membrane conductivity levels are measured within the same current density operating range, and they are linearly proportional to one another, showing that membrane water content is proportional to current density. The SSFFP, IFFP, and SPFFP configurations include almost the same amount of liquid water in respective sections; however, the PFFP includes less water than the other configurations. The proportional linear relationship of membrane conductivity described above and high levels of water content are easily observable [93]. Therefore, it can be predicted that water flooding can occur within the channels. Water content levels play an important role in limiting internal membrane resistance; meanwhile, high water content levels are related to high levels of conductivity. In this simulation model, when the maximum water content levels reaches a value of 14, the maximum degree of membrane conductivity is approximately 12.

Additionally, because flooding phenomena degrade performance due to the presence of liquid water within the channels, a decline in membrane conductivity does not occur.

Polarization curves corresponding to four flow field patterns are calculated and classified into activation, ohmic resistance, and mass transport loss regions. The activation loss regions of the four configurations are identical and range from 0.762 V to 0.767 V, and ohmic resistance loss regions of the SSFFP, IFFP and PFFP range from 0.440 V to 0.466 V. However, the ohmic resistance loss region only appears at 0.139 V in the case of the SPFFP, and the mass transfer loss region does not exist. This may result in water flooding as a result of low water discharge levels. The mass transport loss region of the PFFP, which has a lower cell voltage, is formed by membranes hydration occurring as a result of excessive water discharging at the outlet as noted in [99].

As described in [93], the flow field based on leaf venation shows appropriate pressure drop, uniform velocity and pressure distribution patterns along channels. Therefore, power density levels can be enhanced. Arbabia and et al. created an innovative bipolar plate design based on the leaf venation patterns for PEM fuel cells. Their research goal was to enhance PEMFC performance by optimizing the design of dimensions and the shapes of flow channels. Consequently, effects of various channels and of their dimensions in different configurations (e.g., parallel, one path parallel-serpentine and three path parallel-serpentine flow channels) have been examined.

The notion of using leaf venation patterns has been presented and tested by a two-dimensional numerical model. Simulation results show that performance can be enhanced by eliminating stagnation points in flow field channels. It has been found that leaf venation patterns exhibit appropriate levels of pressure loss and uniform pressure levels and velocity distributions along channels. Therefore, in using the new pattern design, power density levels can be improved by up to 8% [5, 93]. In addition, less pressure is lost when using this pattern than when using other conventional patterns, leading to an increase in fuel cell efficiency as clearly noted in [93].

3.3. Effects of geometrical characterizations of serpentine flow fields on fuel cell operations

Mass transport can be optimized by designing a suitable PEMFC flow field configuration to enhance diffusion and convection. An effective design facilitates uniform reactant transport into catalyst layers in which electrochemical reactions take place; this results in uniform current density distribution and reduces thermal stress acting on the membrane, which is the most fragile element. In addition, the geometrical characterization of the serpentine flow field is one of the solutions to improve PEMFC performance in regards to pressure drop patterns, water discharge levels, the maximum voltage of fuel cells, and uniform distributions of current density observed over active surface areas. In [103], fuel cell channels of three different heights and widths are applied to a serpentine channel with a width and height of 1 mm and 0.34 mm, respectively. As channel heights increase, pressure drop declines and limits friction losses and liquid water accumulation occurring on both the anode and cathode side.

Seven serpentine flow fields with 5 passes and 4 turns were applied in the present work with similar boundary conditions as those described in [103]. The simulations were conducted to compare fuel cell parameter characteristics of the original design of case #1 with the height changes of cases #2-4 and the width changes of #5-7. Performance-related parameter distributions of case #1 are compared to cases #2-4 when channel heights are changed at a current density of 0.6 A/cm^2 on average. The channel heights of cases #2-4 are 0.5, 0.67, and 0.83 mm, respectively; meanwhile, the base height design of case #1 is 0.34. Generally, pressure levels acting on the anode and cathode decrease from the inlet to the outlet due to pressure losses generated from frictional and bending losses occurring in the channel [103]. As the channel height is increased, pressure drop levels are reduced due to the presence of a later cross-sectional area. The pressure loss occurring at the reference location between neighbouring channels should be substantial, and a remarkable pressure gradient much higher than that applied in the channel direction is applied across gas diffusion layers, generating a considerable cross-leakage flow between neighbouring channels. This flow spurs considerable convection processes in the electrode, bringing reactants to the catalyst layers and discharging liquid water from the channels and electrodes. This flow improves overall fuel cell performance. The water content of the membrane positioned under rib areas is generally higher than that measured under adjacent channel areas, as a large volume of formed water between the GDL and the rib is absorbed into the membrane through the under-rib convection phenomenon. This phenomenon involves a similar process as that of the cross-leakage flow. In addition, water levels within the membrane improve from the inlet to the outlet due to a decline in total pressure. Regarding current density distributions of the MEA surface corresponding to the channel heights of cases #1-4 at I = 0.6 A/cm^2, local reference current density levels decline from the inlet to the outlet because gas concentrations decrease in this direction. As all of the simulation cases involve the same electrochemical reactions, current density distributions are left almost unchanged. When increasing the channel height, the obtained cell voltage decreases slightly from 0.568 to 0.565, 0.564, and 0.563 V for cases #2-4, respectively, at I = 0.6 A/cm^2 [103].

The local current density level decreases from the inlet to the outlet due to a reduction of reacting gas concentrations observed along this direction in each simulation case. However, the current density measured at the rib area is lower than that of the inlet area but higher than that of the outlet area in case #7. As case #7 employs the smallest rib width, reactants transferred into the under-rib region due to under-rib convection cannot react sufficiently and in turn leak out to the neighbouring channel of the inlet area; however, remaining reactants improve the current density of the rib area at the outlet. The current density measured under the rib region is higher than that measured under the channel region, facilitating the mass transport of reactants due to an improvement in under-rib convection resulting from pressure differences observed among neighbouring channels. Therefore, when the channel width is increased, the cell voltage decreases from 0.568 V in case #1 to 0.566, 0.561, and 0.551 V for cases #5-7, respectively. The voltage and power density curves of all simulation cases show that cell voltages and power densities of the simulation cases differ, and these differences are proportional to the decrease in current density observed. At 1.1 A/cm^2, average current density levels of the cell voltage and power density of case #7 are respectively 0.266 V and 0.293 W/cm^2, denoting declines of approximately 16.54% and 16.38%, respectively.

3.4. The role of serpentine configurations constructed with sub-channels and bypasses for improving

PEMFC performance

These are simple designs requiring the lowest pressure drop levels by equally distributing gas flows into several parallel paths [5-6]. However, when flow resistance is not maintained at the same levels in every channel, a non-uniform distribution of reactants may form [5-6, 99]. The presence of a convective flow in under-rib regions supports a more effective utilization of electrocatalysts by improving reactant concentrations and by facilitating liquid water discharge in these regions [24]. Some experimental results show that higher levels of GDL permeability enhance the PEMFC performance within serpentine flow fields [100] and limit pressure loss [101]. Uniform temperatures should also help control the operation and long-term durability of PEMFCs.

Flow-field configuration design plays an important role in enhancing mass transfer and water management efficiency, and thus several efforts have been made to optimize flow-field design to guarantee strong and stable fuel cell performance [104-106]. The occurrence of under-rib convection supports the more effective utilization of electrocatalysts by improving reactant concentrations and by facilitating liquid water discharging in these regions [98]. Experimental studies have concluded that higher levels of GDL permeability enhance PEMFC performance and limit pressure losses [100]. It should be noted that the temperature distribution also plays an important role in the operation and enhancement of the long-term durability of PEMFCs. In [98], a simulation flow-field design based on serpentine flow-field patterns and under-rib convection phenomena is presented. The design generates an innovative flow field by inserting sub-channels and bypasses into the conventional serpentine flow field to enhance fuel cell performance. We know that under-rib convection occurring during fuel cell operation results from a pressure difference between neighbouring channels. To offer a better account of this flow feature, under-rib convection phenomena of the new flow-field design (SFFSB) are compared to those of the conventional flow-field design (CASFF) described in [98]. Results show that the under-rib convection flow direction of the new configuration design is significant and may even become dominant relative to with the volume of remaining flows in the flow channel.

Simulation studies were performed on the CASFF and SFFSB flow-field designs as shown in [98], and all the simulations were conducted under operating and initial conditions similar to those described in [98, 103]. PEMFC operation was analysed using simulation models for electrochemical reactions and transport phenomena, which are fully coupled with the equations given in [98, 103, 106]. As a result, operating parameters were profiled and quantitatively compared from the same reference location. Operating parameters used include the mass fractions of hydrogen and oxygen, membrane water content levels (λ), levels of net water flux measured for each proton (α), the mass fraction of liquid water, total pressure levels, temperature levels, current density levels, and voltage and power density curves. These are evaluated to determine the best flow-field design that enhances PEMFC performance.

Under-rib convection can be considered an additional flow because the convection phenomenon occurring through GDLs is designed to improve the reactant concentration measured in under-rib regions and to discharge liquid water from these regions; this ensures more uniform reactant concentration distribution. For the anode side of the CASFF, generally uniform velocity vectors can be observed at the main channel and rib area, in which gas flows in the same direction; however, a minor change occurs from the inlet to the outlet. At turn-rib areas (the last rib or last channel of each section), velocity vectors are dramatically increased due to a strong pressure difference observed between neighbouring main channels. In addition, on the cathode side, under-rib convection is generated from the inlet to the outlet due to the presence of a high stoichiometry ratio, and high-velocity vectors can be observed at adjacent rib and turn-rib areas. In addition, in this case, the rib width is reduced, therefore increasing gas permeability and gas diffusion forces, as the addition of sub-channels changes the flow direction of under rib convection. Consequently, velocity vectors of the anode side are high the main channel inlet and the under-rib convection flow direction converges to the sub-channel through the convection flow, as the pressure level measured at the main channel is higher than that measured from the sub-channels. Uniform velocities at the main channel outlet can be observed, resulting from a decrease in pressure. On the cathode side, under-rib convection occurs at different levels but exhibits similar tendencies as those of the anode side. First, it is generated, and the under-rib flow direction is then changed from sub-channels to main channels at the channel outlet because of the high stoichiometry ratio. This results from an increase in pressure, and, in turn, the reactants travel through sub-channels to reach the outlet. Therefore, the flow direction changes towards the main channel to facilitate smooth discharge [98]. We can clearly observe differences between the representative under-rib convection flow direction and liquid water transfer mechanisms of the conventional flow field and new flow-field design. In addition, membrane water content levels of the SFFSB configuration has smaller differences between the main channels and ribs than those of the CASFF configuration, as under-rib convection occurs from the main channel to the neighbouring rib and then moves from the inlet to the outlet channel while liquid water gathers and discharges into the sub-channel [98].

Generally, the local current density also decreases along the channels from the inlet to the outlet due to the consumption of reactants. In the case of the SFFSB configuration, reacting gases transferred into the under-rib region by under-rib convection enhancement does not sufficiently react and leak out to the neighbouring main channel. However, at the outlet remaining reactants improve the current density of the rib area. In addition, the current density (I) is directly proportional to the membrane conductivity as noted in [102-103].

The current density difference between the inlet and outlet of the SFFSB configuration is less than that of the CASFF configuration due to the membrane water content difference between two cases, as the membrane water content affects membrane conductivity. The uniform current density distribution of the SFFSB also reduces the mechanical stress of the MEA and therefore extends fuel cell lifetime.

3.5. Different designs of anode and cathode flow fields for enhancing fuel cell performance

As noted above, a new serpentine flow field with sub-channels and bypasses (SFFSB) enhances the under-rib convection phenomenon. When the reactants at all channels move in the same way, under-rib convective flows move reactants from the main channels into the sub-channels, and this not only mitigates pressure drop processes but also improves gas supply uniformity and water diffusion. The current and power density maximization of the SFFSB was enhanced significantly due to under-rib convection enhancement relative to that of the CASFF. However, operation conditions of the anode and cathode sides are different, resulting in different patterns of water formation and discharge. Therefore, it is not suitable to apply the same flow-field configuration for both the anode and cathode. This means that when designing a flow field to limit water flooding occurring on the cathode side, anode drying can occur on the anode side. Therefore, it is recommended that a flexible flow field be applied to the anode and cathode sides. In [5] dynamic simulations were conducted to compare four simulation cases when CASFF and SFFSB configurations were flexibly applied to anode and cathode bipolar plates with the same boundary conditions [5-6]. Four configurations are described: configuration I, in which CASFFs were applied to the anode and cathode; configuration II, in which SFFSB and CASFF were applied to the anode and cathode, respectively; configuration III, in which SFFSBs were applied to the anode and cathode; and configuration IV, in which a CASFF and an SFFSB were applied to the anode and cathode, respectively [5]. Governing equations of the simulation models were solved using commercial 3D software ANSYS Fluent® 14.5, a commercial finite volume technique solver that uses source terms for species transfer equations, heat sources and liquid water formation [5, 101]. In this simulation, the following assumptions were applied: (1) the fuel cell operates under steady-state conditions, (2) isothermal boundary conditions are applied to external walls, (3) reactant flows within the fuel cell are laminar, (4) reactants and products are considered ideal gas mixtures, and (5) the electrode is assumed to be an anisotropic and homogeneous porous medium. Furthermore, the performance of the simulation fuel cells was measured by comparing polarization and power density curves while controlling operating conditions related to temperatures, pressure levels, and mass flow rates of the reacting gases [5].

The distribution of the current density of the MEA surface corresponds to flow-field configurations I-IV at an averaged current density of 1.0 A/cm^2 [5]. Generally, the current density measured at the membrane surface reduces from the inlet to the outlet due to the reduction of reacting gases. As different flow-field designs spur different electrochemical reactions, the current density distributions of different cases are changed. The cell voltages of flow field configurations I-IV measured at a current density levels of 1.0 A/cm^2 are 0.5199, 0.5210, 0.5588 and 0.5599 V, respectively. Variations in cell voltages observed between the four simulation cases may result from pressure drop, water distribution and membrane conductivity differences, which relate directly to water content and liquid water saturation levels of the catalyst and membrane [5].

Polarization and power density curves of flow-field designs I-IV were compared in the present study. The results show that the power densities of configurations III and IV are higher than those of flow field configurations I and II. The highest power density levels corresponding to configurations I-IV are 0.5199, 0.5278, 0.6122, and 0.6175 W/cm^2, respectively. When applying the SFFSB configuration to the cathode bipolar plate, the output power density level is increased because under-rib convection supports a more effective utilization of electrocatalysts by improving the reactant mass transfer rate from flow channels to inner catalyst layers and by dramatically limiting water flooding occurring at the cathode side.

Water management strategies play an important role in the optimization of operating parameters of PEMFCs in enhancing their performance because too much water at any location will restrict electrochemical reactions; however, the presence of too little water will lead to an increase in membrane resistance. Water content levels were measured at the membranes, anode catalysts, and cathode catalysts of the four simulation cases corresponding to flow field configurations I-IV. In general, water content levels improve from the anode to the cathode and reach a maximum value at the cathode catalyst surface because the water content of the membrane and anode catalyst are decreased with an increase in current density [5, 6]. However, the opposite trend is observed in the cathode catalyst, in which water content levels improve with an increase in current density. These phenomena occur because when increasing current density levels, the amount of water in the cathode catalyst increases because back diffusion is not strong enough to compensate for electro-osmotic drag occurring during anode drying, spurring faster progress than of the discharge water velocity [5, 9]. In fully humidified conditions, a membrane water content value of λ=14 is appropriate as noted in [5]. Therefore, flooding phenomena normally occur at a λ value of higher than 14 [7]. All of the simulation results show that average water content levels within the membrane do not exceed 14; thus, water flooding is predicted not to be significant along this surface area. However, this may still occur within cathode catalyst areas where water content levels are very high; meanwhile, the water content of anode catalysts is significantly less than λ=14. These patterns are clearly illustrated by an increase observed in the average water saturation of the cathode catalysts and in gas diffusion layers with an increase in current densities observed in simulation cases I-IV. As a result, the averaged water saturation levels of configurations I and II are dramatically higher than those of configurations III and IV. Consequently, cathode flooding occurring in configurations I and II is more serious than that observed in the other configurations. This phenomenon inhibits reactant transference by blocking pores in porous GDLs and by covering active sites in catalyst layers. The impact of cathode flooding exceeds the ohmic overpotential value due to the high relative humidity of the reactants; therefore, the power density of configurations III and IV is higher than that of configurations I and II when compared over a similar current density range.

3.6. Effects of gas flow directions on fuel cell operation

Flow-field design is an important factor to consider when enhancing fuel cell performance. However, the direction of reactants also directly impacts fuel cell operating characteristics, as it also shapes transport phenomena, the uniform reactant distribution, and water management. Many studies have focused on evaluating the effects of gas flow directions on fuel cell operation. The results given in [108] show that fuel cell performance can be dramatically enhanced by optimizing the supplied gas flow direction. Four simulation cases corresponding to various reactant directions were numerically performed. The cases correspond to combinations of supplied reactant directions. Accordingly, the directions of gases moving within the anode and cathode inlet were initiated through co-flows, counter-flows, and interleaved flows for evaluation.

3.6.1. Impact of gas flow directions on water formation and distribution

During the operation of a fuel cell, water is produced through the reaction of fuels and oxidant. This water can exist in liquid phase due to low PEMFC operating temperatures. During PEMFC operation, fuel cell water content can be maintained if the flow-field design of the fuel cell is optimized. The effect of flow fields on water management were simulated by solving governing equations as described in [108]. This research showed liquid water distributions measured from different areas of the fuel cell. Data are compared across four case simulations at 1 A/cm^2 of the current density. Consequently, water distributions of all simulation cases are very low on the anode side. However, large differences are observed on the cathode side depending on gas flow directions involved. For instance, water liquid levels observed in case (a) increase from the left-hand side to the right-hand side as inlet gases move from the left to the right along the channels. The pattern is reversed when gas flows from the right side to the left side in case (b). Meanwhile, a uniform water distribution is observed in case (c) and especially in case (d) when the gas flow directions of adjacent channels are mostly in opposite directions [108]. In general, water saturation levels vary depending on the operating temperature; corresponding average values arranged in ascending order are as follows: case (d), case (c) case (b), and case (a). Moreover, temperatures are very high on the cathode side and especially within the outlet area. These phenomena occur due to effects of gas flow directions and PEMFC operation characteristics. Accordingly, water on the cathode side is generated through reactions of the cathode catalyst and through water transformation occurring on the anode side due to electro-osmotic drag caused by proton transport. Water is also transferred from the cathode to the anode by back diffusion flux. However, at high current densities, the electro-osmotic drag normally prevails over back diffusion processes at high current densities; as a result, the anode will tend to dry out, which can increase the ohmic resistance and lead to a reduction in cell voltage. On the other hand, excess water on the cathode side is responsible for cathode flooding and prevents the oxygen from being transported to the catalyst layer. This can result in a decline in fuel cell performance [106].

3.6.2. Impacts of gas flow directions on fuel cell performance

The impacts of gas flow directions on fuel cell performance were described in [108], it compared current density distributions of the MEA surface and the fuel cell performance of the four simulated cases. Generally, current density levels observed in case (a) degrade from the inlet to the outlet due to a decline in reactant concentrations. For the opposite inlet and outlet gas direction (case b), high current densities can be observed in central areas. However, for cases (c) and (d), when inlet gases move in alternating directions, high current density areas appear on both sides of the fuel cell. In addition, corresponding current density distributions are more uniform than those of cases (a) and (b), as these flow directions improve convection flows travelling from the channels to adjacent areas. The results also show that density distributions of the four simulation cases are different because the different flows spur uneven electrochemical reactions. At the averaged current density level of 1 A/cm^2, the cell voltages of cases (a), (b), (c) and (d) are 0.629, 0.604, 0.668, and 0.692 V, respectively. The highest difference observed in power density levels of the four simulation cases is that of case (d) and is approximately 17% greater than that of case (a). As the current density was controlled in this simulation, differences in cell voltages observed between these cases were affected by the flow-field design, creating different distributions of operating parameters. This means that in comparison to the other flows, flow field case (5) was the least effective at enhancing fuel cell performance because the counter-flow plays a limited role in distributing gases and liquid water across the fuel cell. Otherwise, when applying the flow-field design of case (d), when the gas direction between adjacent channels is alternated, the performance of the fuel cell is significantly enhanced [108].

In a similar study [107], Moosa Ashrafi and et al. evaluated impacts of flow-field orientation on water management in serpentine PEMFCs. The authors focused on finding the best serpentine flow-field flow direction that limit the amount of parasitic power needed for pressure supply systems. Of the configurations simulated, the configuration with cells and channels respectively vertically and horizontally oriented generated the lowest pressure drop value due to effects of gravity on discharging liquid water. However, the configuration with cells and channels vertically- and horizontally-oriented, respectively, spurred the highest levels of pressure loss due to the formation of long plugs along vertical channels [109].

4. CONCLUSION

This work provides a review of the effects of flow-field design on water management and fuel cell operation characteristics. Various configurations of flow fields were applied to find the best flow-field design that enhances fuel cell performance based on both simulations and experiments. With identical active areas and operating conditions, the serpentine flow field configuration operates better than other flow field configurations. In the IFFP, water content levels improve at high current densities, and water behaviour is unstable in outlet channels. In the PFFP, excessive water discharge levels result in membrane dehydration whereas in the SPFFP, flooding occurs due to uneven flow circulation. The numerical optimization of flow field configuration applies mass transfer and electrochemical reaction characteristics to support qualitative assessments of pressure levels, water management systems, and current density levels prior to experimentation.

In addition, geometrical characterizations of serpentine flow field configurations of various heights and widths were performed to investigate pressure drop distributions; membrane water content levels; and liquid water mass fractions of electrodes, temperatures, pressure distributions, and current density levels of active surfaces. When the channel height exceeds that of the original design, the total level of pressure loss declines; this results in the reduction of BOP loads and liquid water concentrations observed at outlets of the anode and cathode. Liquid water generation at the anode outlet caused by back diffusion is accelerated as the channel height increases. When channel widths are wider than that of the original design, pressure drop is mitigated and the liquid water discharge rate increases. The impact of increases in channel width on water discharge is greater than that of an increase in channel height. This can lead to membrane dehydration and thus can affect cell performance and lifetime. The results obtained from this work are expected to be applied to design an efficient serpentine flow field channel based on the insertion of sub-channels and by-passes.

In comparison to the CASFF configuration, the SFFSB configuration is characterized by low pressure levels at the entrance, and it exhibits operating characteristics similar or identical to those of the CASFF by gradually reducing the pressure rate as reacting gases move closer to the outlet. A pressure difference can occur as reacting gas diffusion stabilizes and as the intensity of under-rib convection phenomena is enhanced by inserting sub-channels. As reactant concentration distributions become more uniform within a fuel cell, the diffusion of reacting gases contributes to the uniformity of current density and temperature distributions generated by electrochemical reactions. Temperature distributions improve in certain parts of the rib, as the cooling rate declines when certain parts of the rib dry out while flow field patterns of under-rib convection shift from main channels to sub-channels, discharging liquid water formed in parts of the rib into sub-channels. Moreover, as water in parts of the rib is discharged into sub-channels, the anode liquid water mass fraction increases due to a reduction of electro-osmotic drag.

The direction of supplied gas flows also directly affects fuel cell operation, as it shapes transportation phenomena, the uniform distribution of reacting gases, and water management. Consequently, PEMFC performance can be dramatically improved by optimizing the supplied gas flow direction. When the gas direction between adjacent channels is alternately changed in the interleaved flow configuration, fuel cell performance is dramatically enhanced relative to that of other flow fields. The counter flow-type configuration exhibits the worst capacity to improve fuel cell performance, as it plays a limited role in distributing gases and liquid water across a fuel cell.

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