



Short communication

Effect of anisotropic electrical resistivity of gas diffusion layers (GDLs) on current density and temperature distribution in a Polymer Electrolyte Membrane (PEM) fuel cell

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ABSTRACT

A two-dimensional two-phase model is used to analyze the effects of anisotropic electrical resistivity on current density and temperature distribution in a PEM fuel cell. It is observed that a higher in-plane electrical resistivity of the gas diffusion layer (GDL) adversely affects the current density in the region adjacent to the gas channel and generates slightly higher current densities in the region adjacent to the current collector. Also, in case of GDLs with high anisotropic thermal conductivity, the maximum and minimum temperatures in a cathode catalyst layer depend on the average current density and not the local current density.

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1. Introduction

Over the past few years, there has been a significant interest in analyzing the behavior of a PEM fuel cell using numerical models with varying degrees of complexity for different operating conditions and parameter values [1]. The effect of isotropic electrical conductivity of the gas diffusion layer (GDL) on fuel cell operation was analyzed by Senn and Poulikakos [2] using a two-dimensional non-isothermal model and by Meng and Wang [3] using a three-dimensional isothermal model. The GDLs are commonly constructed of carbon fibers, either in woven or paper form. Electron micrographs of GDLs [4] suggest that the carbon fibers are preferentially oriented in the in-plane direction. Also, thermal and electrical conductivity measurements for certain GDLs [5,6] reveal a high degree of anisotropy. The effect of anisotropic electrical conductivity of the GDLs on the reaction rate in the cathode catalyst layer was analyzed by Sun et al. [7] using a single-phase, isothermal model. We previously analyzed the effects of anisotropic thermal conductivity of the GDLs on the temperature distribution [8] and polarization behavior of a PEM fuel cell [9] using a two-dimensional, two-phase model. In the present work, we extend our analysis to examine the effects of an anisotropic electrical resistivity of the GDLs on current density and temperature distribution, thus

further refining the two-dimensional, two-phase model previously developed.

2. Model formulation

The model used in this work accounts for two-phase flow of reactants, products and ionic species, as well as the generation and transport of heat. The two-dimensional computational domain used in our work is shown in Fig. 1 along with a cross-section showing flow channels, GDLs and membrane. A detailed description of model formulation, constitutive equations and boundary conditions can be found in our previous work [9]. In addition to the model equations described previously [9], we apply:

$$\nabla(\sigma^{-1}\nabla\phi_s) = j \quad (2.1)$$

to solve for the solid-phase potentials in the catalyst layers and GDLs. The boundary conditions at the interfaces of membrane/catalyst layer, anode GDL/bipolar plate and cathode GDL/bipolar plate are, respectively, given by

$$\nabla\phi_s = 0 \quad (2.2)$$

$$\phi_s = U_o - V_{\text{cell}} \quad (2.3)$$

$$\phi_s = 0 \quad (2.4)$$

A detailed description of the source terms j , baseline parameter values and numerical scheme is available [9].

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Nomenclature

GDL gas diffusion layer
 L_x thickness of GDL (m)
 L_{y1} half width of gas channel (m)
 L_{y2} half width of current collector (m)
 R electrical resistance (Ω)
 U_o open circuit potential (V)
 V_{cell} cell voltage (V)

Greek letters

σ electrical resistivity ($\Omega\text{ m}$)
 ϕ_s solid phase potential (V)

Subscripts

xx through-plane
 yy in-plane

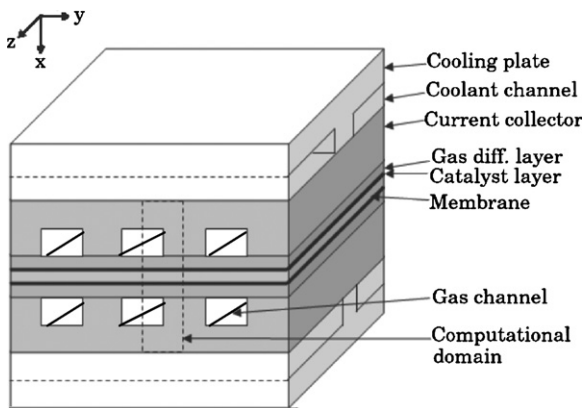


Fig. 1. The computational domain and schematic of a PEM fuel cell.

The modified model was validated against the experimental polarization curves measured by Mench et al. [10]. The values of different parameters used for model validation are given in Table 1. Additionally, the cathode reference exchange current density was used as fitting parameter [11], along with the catalyst layer porosity. The experimental polarization curves at different distances from the inlet [10] along with the model predictions are shown in Fig. 2. It can be seen that even with a two-dimensional model the polariza-

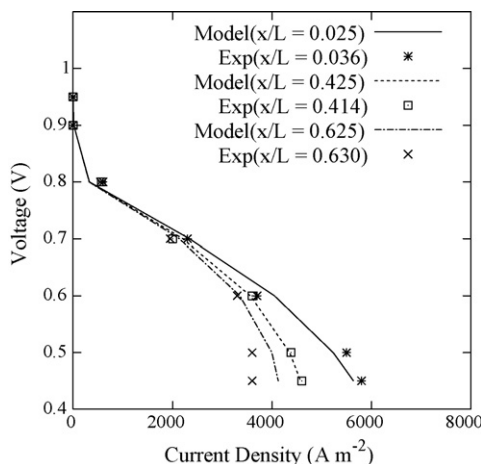


Fig. 2. Comparison of experimental and model polarization curves.

tion behavior at different distances from the inlet can be predicted with a good degree of accuracy. Experimental data, used to verify the local current density and temperature distributions shown in Section 3 in this work, are not available in the open literature. However, the trends in variation of local current density shown in Fig. 3 are similar to the trends predicted recently by Zhou and Liu [12] using a three-dimensional model. Thus, the model and its numerical implementation presented in this work produce results that are similar to other computational modeling approaches of fuel cells.

3. Discussion of results

As discussed in our previous work [9], we use a two-phase model to account for the adverse effects of liquid accumulation in the GDLs and catalyst layers. The effects of multicomponent transport of reactants and water vapor on electrochemical reaction rates and ionic conductivity are also included. The baseline parameter values are same as those used in our previous work [9]. Also, typical values for the in-plane and through-plane electrical resistivities of GDLs are $5.8 \times E - 5\ \Omega\ m$ and $80 \times E - 5\ \Omega\ m$, respectively [5]. Thus, the electrical resistivities of the GDLs are highly anisotropic and low in magnitude. Thus, the GDLs are very good electrical conductors. In the present work, we present a parametric analysis of the possible effects of variation of electrical resistivities on the current density and temperature distribution in a fuel cell. Also, for the purposes of this work, the term ‘average current density’ refers to the current density averaged over the total active area of the fuel cell.

3.1. Effect on current density

The effect of varying the in-plane electrical resistivity of the GDL on current density is shown in Fig. 3 for a low value of through-plane resistivity of the GDL. As expected, the average current density decreases with increasing in-plane electrical resistivity of the GDL. Fig. 3 also shows that, in the region directly exposed to the gas channel, the local current density decreases significantly with increasing in-plane resistivity of the GDL. However, the local current density

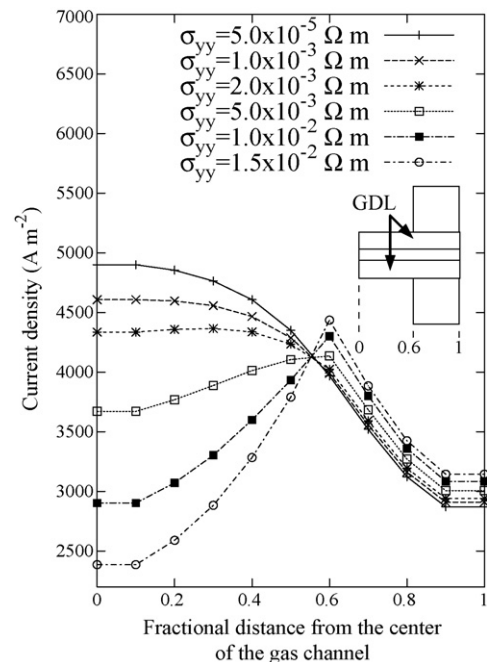


Fig. 3. Variation of local current density with in-plane electrical resistivity, with an through-plane electrical resistivity of $\sigma_{xx} = 5.0 \times 10^{-5}\ \Omega\ m$.

Table 1
Model parameters and properties

Quantity	Value
Gas channel length	1.577 m [10]
Gas channel width	$2.16 \times E-3$ m [10]
Current collector width	$0.89 \times E-3$ m [10]
Active area	$50 \times E-4$ m ² [10]
Membrane	Nafion® 112 [10]
Gas-diffusion layer thickness	$350 \times E-6$ m [15]
Catalyst layer thickness	$10.0 \times E-6$ m
Height of the symmetrical section	$1.525 \times E-3$ m
Anode humidification temperature	353 K [10]
Cathode humidification temperature	353 K [10]
Anode inlet stoichiometry	$1.875 \times E4$ A m ⁻² equiv [10]
Cathode inlet stoichiometry	$1.125 \times E4$ A m ⁻² equiv [10]
Coolant water temperature	353 K (assumed)
Cathode inlet pressure	1.5 atm [10]
Anode inlet pressure	1.5 atm [10]
Gas-diffusion layer electrical resistivity	
Through-plane	$80.0 \times E-5$ ohm-m [5]
In-plane	$15.4 \times E-5$ ohm-m [16]
Through-plane thermal conductivity of gas-diffusion layers, k_{xx}	0.22 W m ⁻¹ K ⁻¹ [10]
Ratio of thermal conductivities, k_{yy}/k_{xx}	20:1 (assumed based on Ref. [15])
Thermal conductivity of the membrane	0.16 W m ⁻¹ K ⁻¹ [13]
Thermal conductivity of the catalyst layer	0.27 W m ⁻¹ K ⁻¹ [16]
Thermal conductivity of current collector (steel)	16.0 W m ⁻¹ K ⁻¹
GDL/bipolar plate thermal contact conductance	$10,000$ W m ⁻² K ⁻¹ (assumed based on Ref. [17])
GDL/bipolar plate electrical contact resistance	41.7 mΩ cm ² [10]
Gas-diffusion layer porosity	0.74 [18]
Maximum interfacial area density	500 m ⁻¹
Catalyst layer porosity	0.15 (fitted)
Hydraulic permeability of GDL	$6.3 \times E-12$ m ² [14]
Hydraulic permeability of membrane	$1.0 \times E-18$ m ² [19]
Hydraulic permeability of catalyst layer	$1.0 \times E-13$ m ² (assumed based on Ref. [14])
Contact angle in GDL and catalyst layer	120°
Hydrogen diffusivity	$0.915 \times E-4$ m ² s ⁻¹ [19]
Oxygen diffusivity	$3.0 \times E-5$ m ² s ⁻¹ [18]
Water vapor diffusivity	$3.0 \times E-5$ m ² s ⁻¹ [18]
Electro-osmotic drag coefficient	1.0 [20]
Transfer coefficient at anode $\alpha_a = \alpha_c$	1.0 [21]
Anode reference exchange current density	$1.5 \times E9$ A m ⁻³ (assumed)
Transfer coefficient at cathode $\alpha_a = \alpha_c$	1.0 V _{cell} < 0.5 V [14] 0.5 V _{cell} > 0.5 V
Cathode reference exchange current density	$1.1 \times E2$ A m ⁻³ V _{cell} < 0.5 V (fitted) $3.0 \times E5$ A m ⁻³ V _{cell} > 0.5 V
Entropy change ΔS for $H_2 + (1/2)O_2 \rightarrow H_2O_{(liquid)}$	-162.4 J mol ⁻¹ K ⁻¹

increases by a small amount in the region adjacent to the current collector. This variation of the current density can be better explained with the help of Fig. 4, which shows the possible paths for transport of electrons from the current collector to the cathode catalyst layer. The electrical resistances for both these paths can be approximately expressed by

$$R_I = \sigma_{xx} \frac{L_x}{L_{y2}} \quad (3.1)$$

$$R_{II} = \sigma_{xx} \frac{L_x}{2} \left(\frac{1}{L_{y1}} + \frac{1}{L_{y2}} \right) + \sigma_{yy} \frac{L_{y1} + L_{y2}}{2L_x} \quad (3.2)$$

Eq. (3.2) reveals that the in-plane electrical resistivity of the GDL adversely affects the transport of electrons from the current collector to the region of cathode catalyst layer exposed to the gas channel, shown by path II in Fig. 4.

In the region of the GDL adjacent to the current collector, the electrons are transported along path I in Fig. 4. Hence, as seen from Eq. (3.1), variation in the in-plane electrical resistivity of the GDL does not directly affect the current density in this region. However, in the region directly exposed to gas channel, the local current density and hence the local rate of electrochemical reaction decreases with increasing in-plane resistivity. This decrease in the electro-

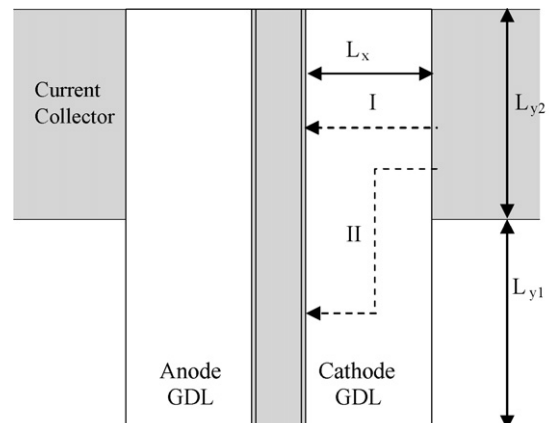


Fig. 4. Schematic representation of transport of electrons in a GDL.

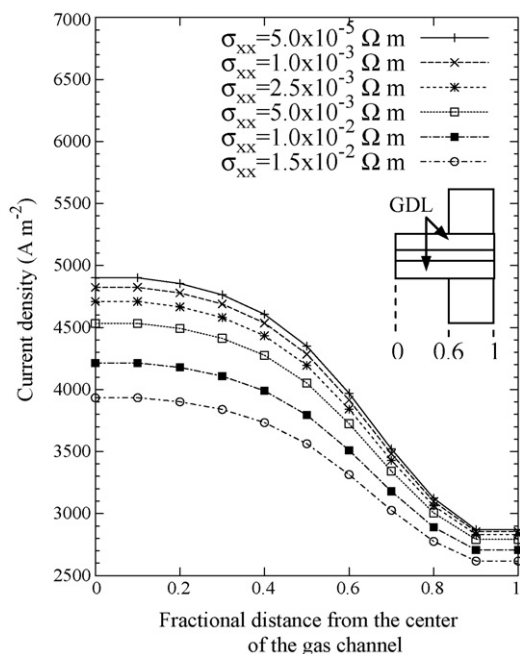


Fig. 5. Variation of local current density with through-plane electrical resistivity, with an in-plane electrical resistivity of $\sigma_{yy} = 5.0 \times 10^{-5} \Omega \text{ m}$.

chemical reaction rate leads to increased concentration of reactants in the region adjacent to the current collector. Therefore, the local current density slightly increases in the region adjacent to the current collector.

The effect of varying the through-plane electrical resistivity of the GDL on current density is shown in Fig. 5. Again, the average current density decreases with increasing through-plane electrical resistivity. Eqs. (3.1) and (3.2) show that the through-plane electrical resistivity affects the transport of electrons from the current collector to the entire catalyst layer. Hence, the local current density decreases with increasing through-plane resistivity of the GDL for the entire catalyst layer.

3.2. Effect on catalyst layer temperatures

It has been shown previously that the maximum temperature in a fuel cell occurs in the cathode catalyst layer [13]. The local temperature in the cathode catalyst layer depends on the heat generation due to kinetic losses, ohmic heat generation and also on reversible heat generation [9]. The electrochemical reaction rate depends on the overpotential, temperature in the catalyst layer, concentration of the reactants and liquid accumulation in the catalyst layer. Lower reaction rate reduces the heat generation rate and hence the local temperature in the catalyst layer. Lower temperatures reduce the electrochemical reaction rate even further by reducing the exchange current density [14] and by allowing more liquid accumulation [9]. In addition, the ohmic heat generation rate depends on the local current density and the reversible heat generation rate depends on the local temperature. The temperature distribution in the catalyst layer is also affected by the thermal conductivity of the GDL [9]. Thus, the local temperature in the catalyst layer is determined by the relative contributions of all these competing factors.

The effects of varying the in-plane and through-plane electrical resistivity of the GDL on temperature distribution in the cathode catalyst layer are shown in Figs. 6 and 7. As expected, the positions of maximum local current density in Figs. 3 and 5 coincide

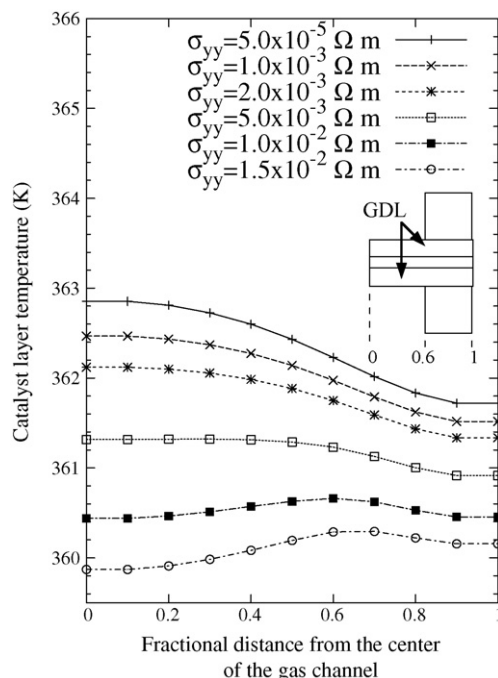


Fig. 6. Variation of catalyst layer local temperature with in-plane electrical resistivity, with an through-plane electrical resistivity of $\sigma_{xx} = 5.0 \times 10^{-5} \Omega \text{ m}$.

with the positions of maximum local temperature in Figs. 6 and 7. Thus, the local current density and hence the local electrochemical reaction rate are the factors determining the location of maximum temperature. However, as shown in Fig. 6, in the region adjacent to the current collector, the local temperatures decrease even though the local current density increases with increasing in-plane resistivity of the GDL as shown in Fig. 3. Figs. 5 and 7 show that the change in the local current density with increasing through-plane resistivity is larger in the region exposed to gas the channel than in the region adjacent to the current collector. However, the change in

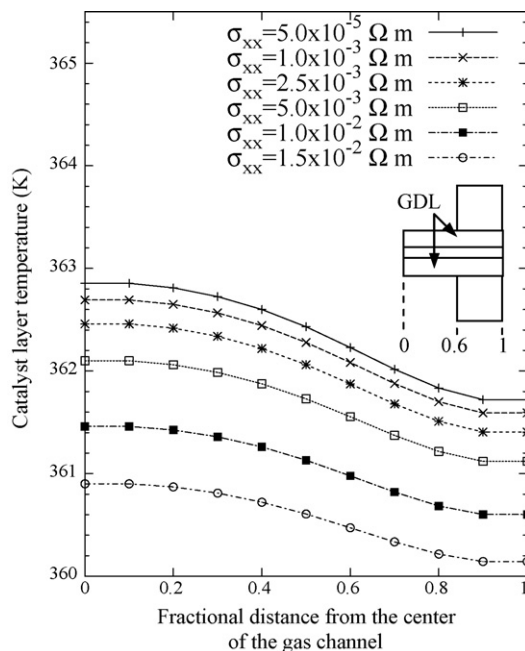


Fig. 7. Variation of catalyst layer local temperature with through-plane electrical resistivity, with an in-plane electrical resistivity of $\sigma_{yy} = 5.0 \times 10^{-5} \Omega \text{ m}$.

the local temperature in the catalyst layer with increasing through-plane resistivity is nearly constant for the entire catalyst layer. Thus, in the region adjacent to the current collector, the local current density is not the dominant factor for determining the local temperature in the cathode catalyst layer. We have shown in our previous work that using GDLs with highly anisotropic thermal conductivity unifies the temperature distribution [8,9]. Such a temperature distribution leads to lower maximum temperature and higher minimum temperature in the cathode catalyst layer. Thus, in case of GDLs with highly anisotropic thermal conductivities, the minimum temperature in the catalyst layer is governed by the in-plane thermal conductivity of the GDL. It can be noticed from Figs. 3, 5–7 that both maximum and minimum temperatures in the catalyst layer decrease with decreasing average current densities even though in some cases the maximum local current densities increase with decreasing average current densities. Thus, for GDLs with high in-plane thermal conductivities, the maximum and minimum temperatures in the cathode catalyst layer depend on the average current density rather than the local current density in the catalyst layer.

4. Conclusions

A two-dimensional, two-phase non-isothermal model developed previously [9] has been extended to account for an anisotropic electrical resistivity of the GDL on current density and temperature distribution. The important conclusions from the study are summarized by:

1. In the region directly exposed to the gas channel, local current density decreases with increasing in-plane GDL electrical resistivity.
2. A higher in-plane GDL electrical resistivity results in a slightly higher local current density in the region directly in contact with the current collector.
3. The local current density decreases with increasing through-plane resistivity of the GDL for the entire catalyst layer. The effect is more severe in the region of the catalyst layer directly exposed to the gas channel.
4. The maximum and minimum temperatures in the cathode catalyst layer are largely governed by the average current density rather than the local current density for a GDL with a highly anisotropic thermal conductivity.

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