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On the relative influence of convection in serpentine flow fields of PEM fuel cells

J.P. Feser, A.K. Prasad*, S.G. Advani

Department of Mechanical Engineering, University of Delaware, Newark, DE 19716-3140, USA

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Abstract

In polymer electrolyte membrane fuel cells, power losses associated with slow reaction kinetics and mass-transport limits can be strongly influenced by convective flow characteristics. Specifically, convection in the form of channel bypass may be utilized to simultaneously increase reactant concentration and reduce product concentration in the catalyst layer, thus reducing the activation and mass-transport overpotentials. An analytical model is developed here to predict the flow pattern and pressure field in general single-serpentine flow field geometries. The model predicts that a significant portion of the total flow through the fuel cell can occur as in-plane convective flow through the gas diffusion layer under realistic operating conditions. Further, by comparing the in-plane rates of diffusive and convective transport it is found that the dominant mechanism depends on the geometric and material parameters of the flow field. In particular, it is found that the relative influence of convection depends highly on in-plane permeability of the gas diffusion layer and channel length, and is relatively independent of gas diffusion layer thickness. By designing fuel cells to utilize enhanced in-plane convection, it is suggested that losses associated with low oxygen content as well as liquid water buildup in the catalyst layer can be reduced.
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Keywords: PEM; GDL; Convection–diffusion; Serpentine; Channel bypass; Flow field

1. Introduction

Polymer electrolyte membrane (PEM) fuel cells utilize specially designed channels integrated within their bipolar plates to distribute reactant gases and remove reaction products. A widely used flow channel configuration for modern fuel cells is the single serpentine. Shown in Fig. 1, single-serpentine flow fields consist of one continuous channel that proceeds through a series of alternating 180° turns. The single-serpentine configuration forces nearly all of the reactants through a single, long channel. In contrast, flow channel configurations such as parallel, interdigitated, and parallel-serpentine hybrids distribute flow over many channels whose individual lengths are much shorter. Consequently, a larger overall pressure drop has to be incurred to generate sufficient flow to satisfy the stoichiometric requirements of a single-serpentine fuel cell.

The larger pressure drop across the single-serpentine configuration presents both challenges and opportunities for cell designers. The obvious disadvantage of such a design is that it increases pumping requirements which adversely affects both system cost and volume. However, the larger pressure drop may be used to contribute favorably to cell performance in two ways. First, it can enhance the ability of the cell to remove blockages such as those created by liquid water produced on the cathode side of hydrogen fuel cells, or by carbon dioxide bubbles produced on the anode side of direct methanol fuel cells. This improves the ability of the fuel cell to operate at high current densities.

Because the flow typically proceeds along the serpentine channel at significant velocity, pressure differences can develop between adjacent channels due to viscous losses. This can lead to a second avenue for improved performance, termed *channel bypass*. Fig. 2 depicts the channel bypass mechanism. A pressure difference between adjacent channels can cause the fluid to "short-circuit" from one channel to the next through the porous gas diffusion layer (GDL) under the lands of the bipolar plate.

* Corresponding author. Tel.: +1 302 831 2960; fax: +1 302 831 3619.
E-mail address: prasad@me.udel.edu (A.K. Prasad).

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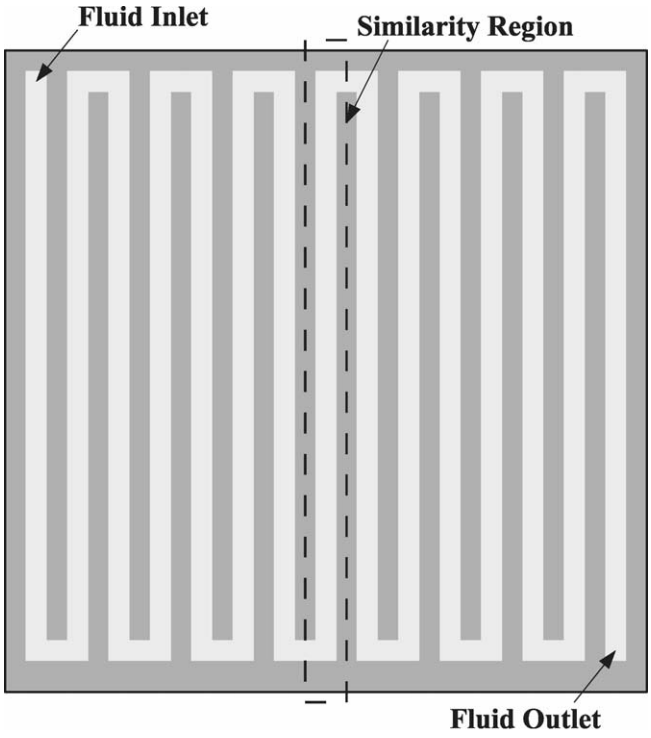

Fig. 1. Diagram of a single serpentine flow field configuration.

In order to understand why channel bypass might benefit fuel cell performance, consider the two primary mechanisms for mass transport in fuel cells, binary diffusion and convection. The chemical species flux due to diffusion j_{diff} can be described as being driven by a concentration gradient. Then according to Fick's law,

$$j_{\text{diff}} = -D\nabla c \tag{1}$$

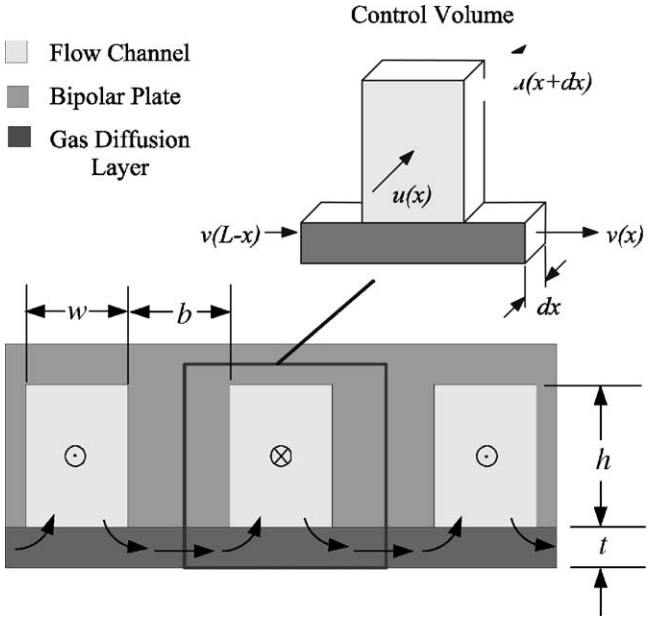

Fig. 2. Schematic of channel bypass (bottom) and control volume used to describe mass balance (top).

where D is the binary diffusion coefficient and c is the species concentration. The key feature of binary diffusion is that a gradient in concentration is required to drive mass transport. In the cathode of PEM fuel cells, this leads to three undesirable consequences. First, it requires oxygen concentration to become higher in the channels than in the catalyst layer which leads to diffusion-limited reactant mass transport; this limit exists because the largest concentration gradient that can possibly occur for a given channel concentration, c_{chan}, corresponds to zero concentration in the catalyst layer, so that $j_{\text{diff,max}} = -D\,c_{\text{chan}}/t$, where t is the thickness of the GDL. Of course, even this limiting flux cannot be reached because the cell will begin to perform poorly due to the low concentration in the catalyst layer. A second, related phenomenon occurs with diffusion-driven water vapor transport; in order to remove water, a concentration gradient must develop so that water concentration is highest in the catalyst layer and lowest in the flow channel. These conditions can favor the premature formation of liquid water and thus fuel cell flooding. Third, diffusion-dominated mass transport causes uneven distribution of current density due to differing diffusion distances; current density directly under the gas channels is high, while current density under the lands of the bipolar plate is significantly less.

In contrast, convection does not require a loss in concentration to drive reactants. Rather, molecules are physically carried at the local velocity, $\tilde{u}$, so that the flux of a particular species due to convection is given by

$$j_{\text{conv}} = c\tilde{u} \tag{2}$$

The net flux of a species due to the combination of convection and diffusion is merely the sum of the two fluxes. Since convection does not require concentration losses, higher reactant concentrations can be achieved in the catalyst layer under convection-dominated conditions. It is proposed that channel bypass is a means by which to enhance cell performance by increasing convective mass transport into the GDL. It is worth noting that the concept of channel bypass is indeed the primary motivation for another successful class of flow channel designs, namely the interdigitated configuration [1]. It is also worth noting that there is at least one counter-argument in the literature which refutes the logic of increased performance by enhanced convection [2], with the claim that increased convection can cause reactant to be used prematurely, thus causing localized concentrations in the catalyst layer which adversely affects the cell potential. Future experiments and computer modeling efforts may be able to distinguish the merits of the arguments for and against enhanced convection. Regardless of the outcome, there is a clear need to know whether fuel cell designs operate in diffusion- or convection-dominated regimes because of the fundamentally different physics involved. The purpose of the current work is to develop an analytical model capable of predicting the flow pattern and pressure field inside a fuel cell based on the single serpentine flow channel configuration. Using this information, the relative importance of convective flow can be determined for various design parameters.

2. Model

Many current serpentine designs employ channels that are approximately 1 mm wide with land regions that are also about 1 mm wide. Thus, even for a small cell area on the order of 10 cm^2, the serpentine makes about 16 180° turns; fuel cells with larger areas can have significantly more turns. Given the repetitive nature of the serpentine geometry, it is expected that after an initial development length, the flow will settle to some periodically repeating velocity field. Then, the analysis can be restricted to a 'unit cell' containing the periodic region (such a region is outlined in Fig. 1). The velocity in the channel is three dimensional; in the most general formulation it is possible to search for the velocity in the primary flow direction, $u(x,y,z)$, as well as the secondary flows, $v(x, y, z)$ and $w(x, y, z)$, which must be present in order for channel bypass to occur. Computer software can be used to solve the full set of Navier-Stokes equations in the flow channels with Darcy's Law applied in the porous medium. While computer solutions can potentially simulate the full three-dimensional flow at high Reynolds number, they are time consuming and can only be performed for a finite number of parameter values. Analytical solutions for the full three-dimensional flow at high Reynolds number would be difficult if not impossible, but under some simplifications, an analytical solution is possible that contains most of the useful information from the computational solution. We restrict our analysis to the cathode side of air breathing fuel cells because (1) the cathode side suffers from higher activation overpotential and mass-transport limitations in hydrogen PEM fuel cells, and (2) due to hydrogen's high molecular diffusivity, the anode side is less likely to be influenced by convection.

This restriction allows two assumptions that greatly simplify the analysis: the assumptions of constant density and viscosity in the gas channel. Of course, neither is strictly true because chemical composition and temperature will vary within the cell. However, air is composed of 78% nitrogen and only 21% oxygen. Thus, even if the chemical reaction completely consumes a fuel cell's oxygen, the majority of the inlet gas would still remain. In practice oxygen is never allowed to deplete entirely as it would severely hinder cell efficiency. Also, while viscosity is strongly dependent on temperature, computer-modeling work indicates that the fluctuations in temperature are small enough to neglect local changes in viscosity [3]. The assumption of constant density and viscosity may also be applicable on the anode side of a direct methanol fuel cell for analogous reasons. In order to further simplify the analysis, we will assume that the magnitude of secondary velocities, v and w, are much smaller than the velocity along the direction of the channel, u. We will also assume that u varies slowly with x and that the pressure p varies slowly with y and z so that the Navier-Stokes equations reduce to the unidirectional form

$$\frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} = \frac{1}{\mu}\frac{\mathrm{d}P}{\mathrm{d}x} \tag{3}$$

The no-slip condition can then be applied to u at the boundaries of the channel cross section. Eq. (3) is of Poisson form and solutions are available for most geometries of importance. Regardless of the specific geometry of the flow channel, the average velocity in a finite width channel can be expressed in the form

$$u_{\mathrm{mean}} = -f\frac{A_\mathrm{c}}{\mu}\frac{\mathrm{d}P}{\mathrm{d}x} \tag{4}$$

where A_c is the cross sectional area of the channel and f is a non-dimensional function of non-dimensional groups which defines the geometry of the channel and may also include provisions for portions of the GDL which protrude into the channel. The term fA_c can be viewed as the 'permeability' of the channel, hereon denoted as k_c. The flow channel geometry most often employed is rectangular. In this case, $A_\mathrm{c} = wh$, where w is the width of the channel and h is the height. The function $f = f(h/w)$ can be analytically computed from the solution of the Poisson equation to be

$$f = \sum_{n=0}^{\infty}\sum_{m=0}^{\infty}\frac{64(-1)^{2(m+n)}}{\pi^6(2m+1)^2(2n+1)^2} \times \frac{1}{(2m+1)^2(h/w)+(2n+1)^2(w/h)} \tag{5}$$

For illustrative purposes, the geometric factor is shown graphically in Fig. 3.

An expression similar to Eq. (4) can be obtained to relate the channel bypass to the pressure drop between adjacent channels from first principles. Fig. 2 shows a characteristic cross-section of a fuel cell. It can be shown that the total flowrate traveling under the land is linearly related to pressure drop between the two channels. Then the average artificial velocity, v_GDL, under a land of width b can be expressed as

$$v_\mathrm{GDL} = \frac{k_\mathrm{eff}}{\mu}\frac{P_\mathrm{high} - P_\mathrm{low}}{b} \tag{6}$$

where the subscript on the permeability takes into account the geometric layout of the problem as well as any difference in the in-plane permeability k_i, and through-plane permeability k_t, of the GDL. However, the effective permeability, k_eff approaches

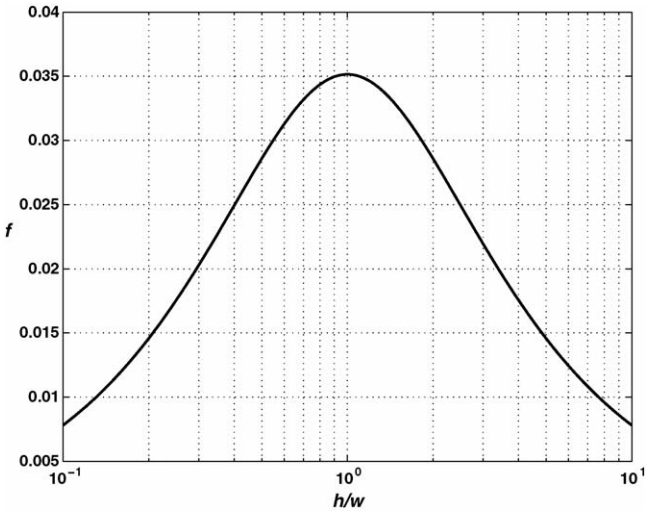

Fig. 3. Geometric factor, f, for a rectangular channel.

the in-plane permeability under the condition

$$\frac{k_i}{k_t}\frac{t^2}{b^2} << 1 \tag{7}$$

A typical value of the ratio t/b is 0.2–0.4. Based on reported values of through-plane and in-plane permeability [4,5] the ratio $k_i/k_t \approx 1$ for several materials of interest. Thus, inequality 7 is satisfied for a wide range of applications.

In order to proceed further, symmetry of the infinite serpentine can be exploited. To obtain the flow in the adjacent channel (whose primary flow is now in the opposite direction), all that is needed are the symmetry relations

$$u_{\text{adj}} = -u(L - x) \tag{8}$$

$$v_{\text{adj}} = v(L - x) \tag{9}$$

$$P_{\text{adj}} = P(L - x) + P(L) \tag{10}$$

where hereon the subscripts on u and v have been dropped and are understood to represent the mean value in the channel and GDL, respectively.

A control volume (shown in Fig. 2) can be defined which encompasses the flow channel and GDL over the width of one channel and has infinitesimal depth in the x direction. The only mass fluxes on the control volumes boundaries come from the u component of velocity in the channel and the v component of velocity in the GDL. Then, for mass conservation

$$A_c\frac{du}{dx} + t(v(x) - v(L - x)) = 0 \tag{11}$$

The expression for $u(x)$ is given by Eq. (4). Using the simplified version of Eq. (6) in conjunction with Fig. 4, the GDL velocities can be obtained as

$$v(x) = \frac{k_i}{\mu b}(P_2 - P_3) \tag{12}$$

$$v(L - x) = \frac{k_i}{\mu b}(P_{2'} - P_{3'}) \tag{13}$$

Using Eq. (9) to relate the pressures in adjacent channels,

$$P_3 = P_{2'} + P(L) \tag{14}$$

$$P_{3'} = P_2 + P(L) \tag{15}$$

This can be used with the continuity equation to arrive at the combined equation

$$\frac{d^2P(x)}{dx^2} + \frac{2}{A_c}\frac{t}{b}\frac{k_i}{k_c}((P(L - x) - P(x)) = 0 \tag{16}$$

If the total change in pressure over the entire cell is given by ΔP_{cell} and the total number of channel passes is N_c, then the boundary conditions are given by

$$P(0) = 0 \tag{17}$$

$$P(L) = \frac{\Delta P_{\text{cell}}}{N_c} \tag{18}$$

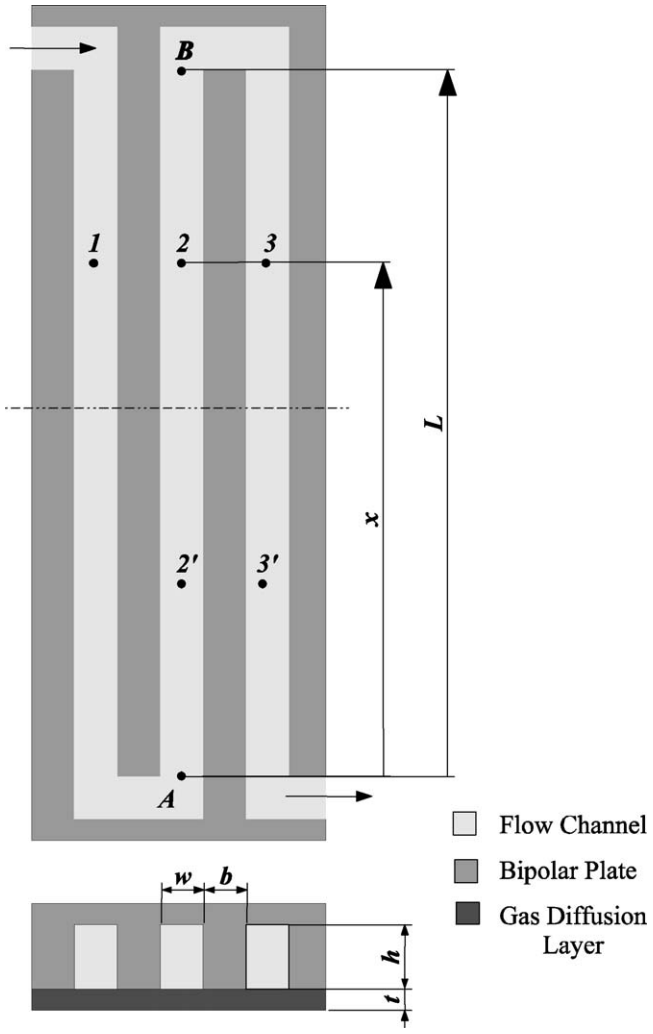

Fig. 4. Geometric description of flow channel and coordinate system.

Eq. (16) subject to the boundary conditions 17–18 admits the solution

$$P(x) = \frac{\Delta P_{\text{cell}}}{2N_c}\left(\frac{\sinh(m(x/L - 1/2))}{\sinh(m/2)} + 1\right) \tag{19}$$

where

$$m^2 = \frac{4L^2}{A_c}\frac{t}{b}\frac{k_i}{k_c} \tag{20}$$

Using Eq. (4), the mean velocity in the channel is then

$$u(x) = -\frac{k_c}{2\mu L}\frac{\Delta P_{\text{cell}}}{N_c}\left(\frac{m\cosh(m(x/L - 1/2))}{\sinh(m/2)}\right) \tag{21}$$

And the mean velocity in the GDL is

$$v(x) = -\frac{k_{\text{eff}}}{\mu b}\frac{\Delta P_{\text{cell}}}{N_c}\left(\frac{\sinh(m(x/L - 1/2))}{\sinh(m/2)} + 1\right) \tag{22}$$

3. Analysis

Using the results of the previous section, it is possible to predict the effect of geometric and material parameters on mass

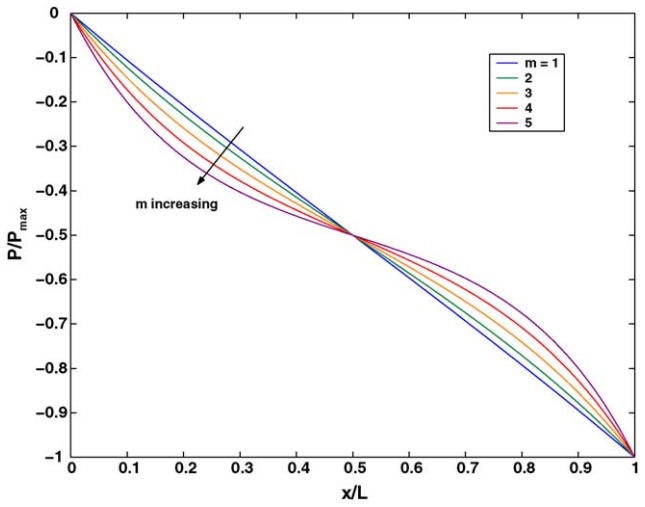

Fig. 5. Variation of pressure with x.

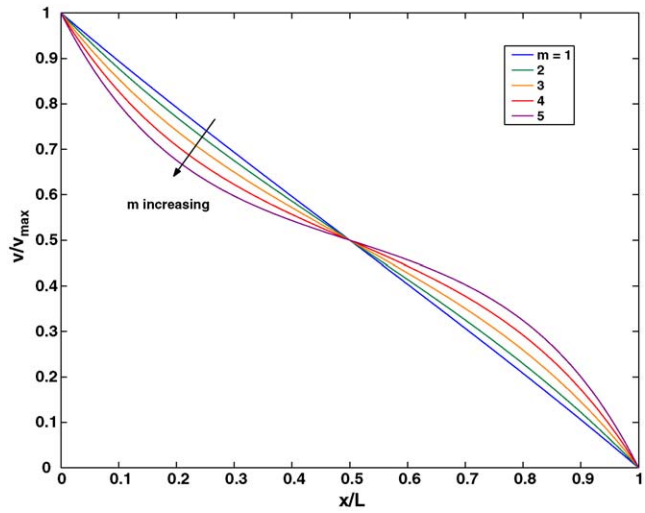

Fig. 7. Variation of GDL velocity v with x.

transport. The shape of the pressure and velocity profiles is dependent on the non-dimensional quantity m, which for many serpentine configurations falls in the range of 0.5–5. The pressure profile along the channel is shown in Fig. 5. When m is small, convective bypass is small, and the pressure drops linearly because all of the gas flows along the channel. For increased values of m, the pressure profile exhibits curvature. It is easier to understand the curvature by looking at the u velocity profile along the channel (Fig. 6). Velocity along the channel is slower near the midpoint; thus, the local pressure gradient is also lower near the midpoint. Likewise, pressure changes most rapidly at the 180° turns corresponding to the maximum channel velocity. The average velocity in the GDL $v(x)$ is plotted in Fig. 7. When the pressure drop is linear (low m), $v(x)$ also varies linearly. As expected, $v(x)$ is greatest at $x = 0$ because that is where the pressure difference caused by viscous losses is a maximum. One interesting observation about flow through the GDL is that the channel-length-averaged velocity into the GDL (normalized by the maximum) is a constant for all values of m.

A particular quantity of interest is the amount of flow, which penetrates into the GDL during each pass. Using the velocity profiles computed in the previous section, the ratio of fluid going around the corner of the serpentine to the flow through the GDL is

$$\frac{Q_{\text{corner}}}{Q_{\text{GDL}}} = \frac{u(x=0)A_{\text{c}}}{t\int_0^L v(x)\,\mathrm{d}x} = \frac{2}{m\,\tanh(m/2)} \tag{23}$$

And the ratio of flow going around the corner to the total flow is

$$\frac{Q_{\text{corner}}}{Q_{\text{total}}} = \frac{2}{m\,\tanh(m/2)+2} \tag{24}$$

Given the large number of dimensionless parameters which prescribe the geometric and material properties of the serpentine network, it is remarkable that the ratio $Q_{\text{corner}}/Q_{\text{total}}$ is only a function of one combined dimensionless parameter, m. Shown in Fig. 8 is the ratio $Q_{\text{corner}}/Q_{\text{total}}$ plotted against the dimensionless parameter m. For small values of m, practically all of the flow travels around the corner of the flow channel. Near $m = 1$, the flow

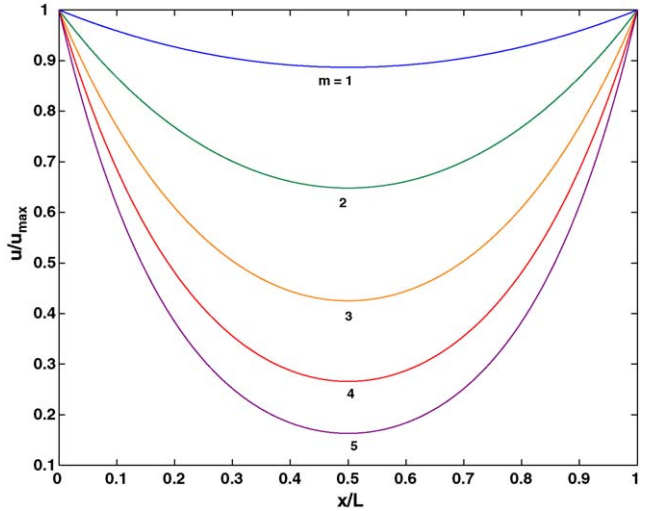

Fig. 6. Variation of channel velocity u with x.

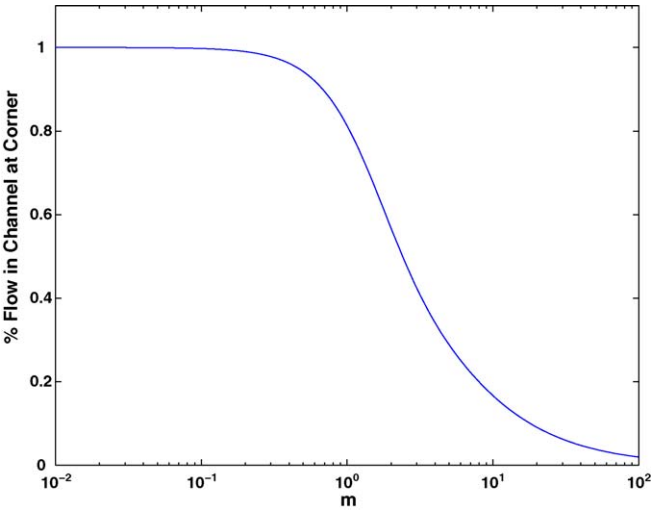

Fig. 8. The fraction of flow along the channel as a function of the parameter m.

around the corner quickly begins to decline, and for m greater than about 2, the majority of flow travels through the GDL. Interestingly, the typical range of m for currently employed cells can be calculated to be somewhere between $0.5 < m < 5$. Thus, for the serpentine geometries used in current fuel cells, the amount of reactant convectively penetrating into the GDL varies quite widely. In one of the most commonly employed serpentine networks, the channel cross-section is square; then m from Eq. (20) takes the form

$$m = \frac{2L}{w^2}\sqrt{\frac{tk_{\mathrm{GDL}}}{f}} \tag{25}$$

From this equation it is clear that m is most sensitive to changes in the channel width, w. However, increasing m by decreasing w is not always preferable as large pressure drops can be incurred. Another way to achieve a higher value of m is by changing the length of the channel, L. To understand why this would be the preferred way of increasing convection under the lands, consider the following example. A small square fuel cell with 10 cm^2 active area would typically have parameters $L = 3.1$ cm, $w = 1$ mm, $b = 1$ mm, $t = 300$ μm, and $k_{\mathrm{GDL}} = 1 \times 10^{-11}$ m^2. From Eq. (25), it is calculated that $m \approx 0.6$ and subsequently that only about 8% of flow travels through the GDL on each pass. However, if the area of the cell is held constant but the channel length is increased to 10 cm (i.e. the active area is made into a 10 cm × 1 cm rectangle), then $m \approx 1.9$ and 41% of flow travels into the GDL on each pass. Although the channel length for each pass is increased, the total length of the serpentine channel remains the same because the active cell area was maintained. Thus, no penalty due to pressure drop is incurred; meanwhile, flow to the GDL is increased substantially. Therefore, there it may be advantageous from this viewpoint to employ rectangular rather than square geometries for single-serpentine flow fields.

While experimental methods such as particle image velocimetry are being pursued to measure velocity fields in fuel cells [6,7], we must currently rely on computational models to quantify such flows with high resolution. We validate our current model against a recent computational study of single-serpentine geometries [8]. Similar to our analytical model, the computational model also employs the assumptions of constant gas density and viscosity and thus does not capture the chemical reaction physics. However, unlike the analytical model, the computational model considers a full three-dimensional treatment of convection through a unit cell of a serpentine network with a range of Reynolds number between 100 and 400. In order to model the interaction of the GDL with the flow channel, the study employs a modified version of the Navier-Stokes equations which uses a momentum source term consistent with Darcy's Law; Figs. 9 and 10 compare computational solutions from [8] with the analytical solution from the current study. Fig. 9 examines the percentage of flow moving around the corner at $Re = 100$ for two different channel lengths. For the analytical solution, this ratio is independent of Reynolds number due to the assumption of creeping flow. However, the figure shows that the analytical solution and computational solutions are in good agreement despite being applied at relatively high Reynolds

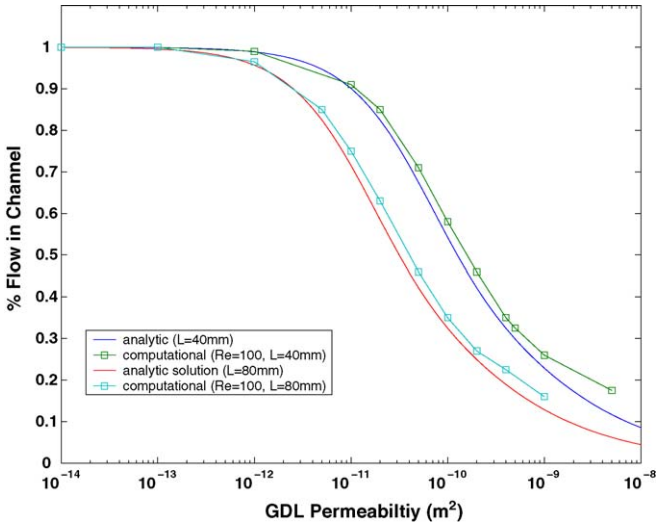

Fig. 9. Comparison of the fraction of the total flow that remains in the channel for the current analytical model and a computational model [8].

number. The analytical solution slightly under-predicts the pressure drop across the land and thus over-predicts the flow through the GDL; by removing the assumption of inequality 7, the agreement can be improved. Fig. 10 shows the anticipated pressure drop over two lengths of the serpentine for the same set of conditions. Again, analytical predictions agree well with the computation; here too the analytical curve deviates slightly due to the assumption of inequality 7.

While it has been shown that proper choice of the dimensionless parameter m can increase the percentage of the flow traveling under the lands, it has not yet been shown that this parameter should influence fuel cell performance. It will clearly not be important if molecular diffusion outpaces transport by convection. Thus, a more important gauge of the influence of convection is the Peclet number which compares the relative importance of convection versus diffusion. Here the Peclet number will be defined in such a way as to show the relative importance of con-

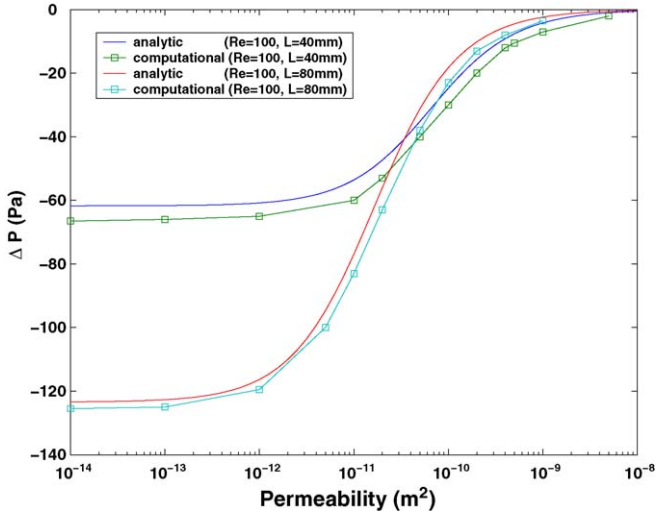

Fig. 10. Comparison of the pressure drop predictions in the current analytical model and a computational model [8].

vection underneath the lands in the in-plane direction and will be denoted $P_{||}$. Then

$$Pe_{||} = \frac{v(x)b}{\varepsilon D} \tag{26}$$

where ε is the porosity of the GDL; inclusion of the porosity term is justified because the actual fluid velocity is always higher than the artificial velocity. However, for most current gas diffusion media, porosities are relatively high (60%–90%) meaning that the artificial and actual velocities are close to one another.

As previously discussed, if convection can be made the dominant mechanism of mass transport in a fuel cell, then reactant concentration in the GDL and likely the catalyst layer can be raised to a level near that in the channel which will improve cell performance. Also, if convection is the primary mechanism of transport at high current densities, then diffusion-limited mass transport can be overcome. Furthermore, channel bypass can provide an escape mechanism for water vapor produced at the catalyst layer although, since the binary diffusion coefficient of water vapor in air is more than twice that of oxygen in air, larger velocities are required to achieve convective dominance for water removal. Substituting Eq. (22) in Eq. (26), the Peclet number can be expressed as

$$Pe_{||} = \frac{2}{\varepsilon}\frac{k_{\text{eff}}}{k_c}\frac{L}{w}\frac{\tanh(m/2)}{m}\left(1 - \frac{\sinh(m(x/L - 1/2))}{\sinh(m/2)}\right) ScRe \tag{27}$$

where Re and Sc are the Reynolds number and the Schmidt number respectively, defined as $Re \equiv u(x = 0)w/v$ and $Sc \equiv v/D$. The Reynolds number can be related to the mass flowrate of air into the fuel cell. For a fuel cell operated at current density i and stoichiometry λ, the Reynolds number is

$$Re = \frac{i\lambda M_{\text{air}}}{4F\gamma_{O_2}\mu}\frac{N_c L(b+w)w}{A_c}\left(\frac{2}{m\,\tanh(m/2) + 2}\right) \tag{28}$$

where M_{air} is the molar mass of air, F is the Faraday constant, and γ_{O_2} is the mole fraction of oxygen in air. For fuel cells employing square active areas, the number of channels N is approximately $N = L/(b + w)$. For analysis purposes, it is convenient to average the Peclet number along the length of the channel. Then,

$$Pe_{||,\text{avg}} = \frac{2}{\varepsilon}\frac{k_{\text{eff}}}{k_c}\frac{L}{w}\frac{\tanh(m/2)}{m} ScRe \tag{29}$$

Unlike the ratio $Q_{\text{corner}}/Q_{\text{total}}$, the Peclet number depends on many parameters. In order to understand the relative importance of convection in current fuel cells, consider changes made to only three of the important variables, the GDL in-plane permeability k_{eff}, the channel length L, and GDL thickness t, while holding all other parameters constant (see Table 1). Also, for the purposes of the example, let the active area and the channel cross-section be square (although, as mentioned earlier, there are compelling reasons not to do so in practice). Figs. 11–13 show contours of Peclet number over a range of channel length and GDL permeability at particular values of GDL thickness. The jaggedness of the contours is not an artifact, but rather a result of setting the number of channels, $N = L/(b + w)$; N is rounded to achieve a discrete value, thus the jaggedness.

Table 1
Parameters used to generate Figs. 11–13

Description	Parameter	Value	Unit
Porosity	ε	0.8	
Channel width	w	1	mm
Fluid viscosity	μ	2.0×10^{-5}	Pa s
Land width	b	1	mm
Stoichiometric ratio	λ	2	
Current density	i	1	A cm^{-2}
Binary diffusion coefficient	D	3.2×10^{-5}	m^2 s^{-1}
Density of air	ρ_{air}	1.2	kg m^{-3}

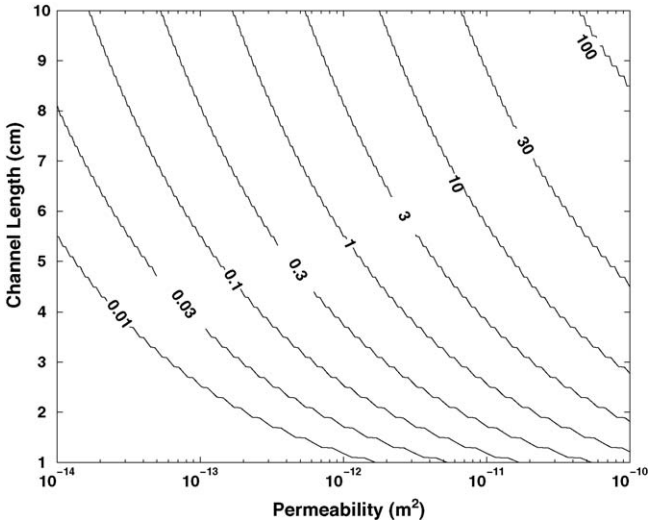

Fig. 11. Relative influence of convection (as determined by the Peclet number) for various GDL permeabilities and channel lengths with GDL thickness fixed at 100 μm.

The most striking feature of Figs. 11–13 is that the Peclet numbers are in the intermediate range. This means that at a particular cell size, the choice of GDL can significantly alter the primary mass transport mechanism. Experimental

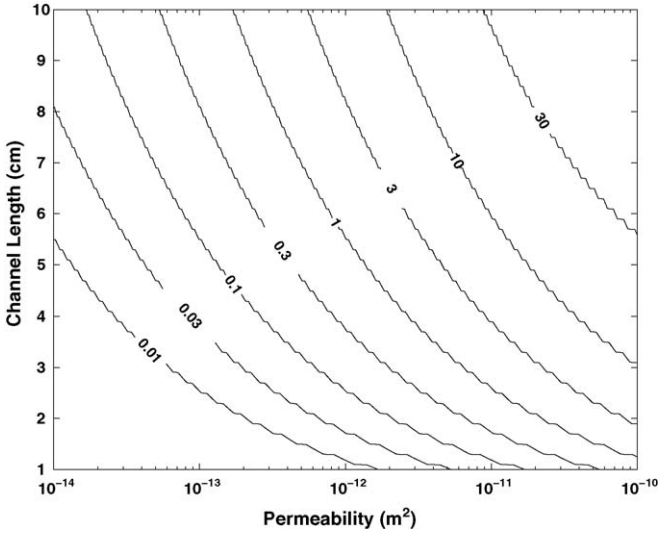

Fig. 12. Relative influence of convection (as determined by the Peclet number) for various GDL permeabilities and channel lengths with GDL thickness fixed at 200 μm.

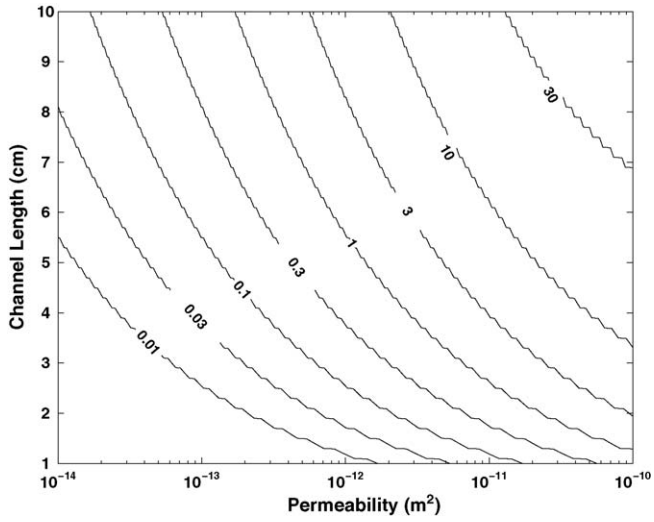

Fig. 13. Relative influence of convection (as determined by the Peclet number) for various GDL permeabilities and channel lengths with GDL thickness fixed at 300 μm.

characterization in our work [9] and elsewhere in the literature, shows that in-plane permeability for commercially available GDL materials can take on a wide range of values (5×10^{-13} m^2–5×10^{-11} m^2). For a GDL at the upper end of that range, the results indicate that any cell with active area larger than 15 cm^2 will be dominated by convection. In contrast, at the lower end of the range it will not achieve convective dominance for any realistic cell size. Thus, in-plane permeability is an important parameter governing fuel cell operation.

A second important result is that the Peclet number is insensitive to GDL thickness over the range of typical use. Despite a 300% change in GDL thickness between Figs. 11 and 13, the Peclet number changes only a few percent. This has important implications for fuel cells since reducing the thickness of the GDL can reduce material cost, stack volume, and the ohmic overpotential. It should be noted however, that if a thin GDL is used under diffusion-dominated conditions instead of convection-dominated conditions, the reactant and product concentration distributions could be highly uneven due to the varying diffusion distances; this would adversely affect fuel cell performance.

4. Discussion

The analysis thus far indicates that under judicious yet reasonable choices of channel geometry and GDL characteristics, a substantial amount of the total flow in a fuel cell can be made to convect through the GDL by the mechanism of channel bypass. Further, by comparing the rates of convections to that of diffusion, it was found that convection could also be made the dominant form of mass-transport. It can be concluded that convection will strongly influence cell performance. One significant weakness of the current model is that it cannot predict the cell performance since it ignores the reaction kinetics; thus, while it is simple to determine whether a given cell will be strongly influenced by convection, it is not immediately apparent what the corresponding boost (or drop) in performance will be. Fortunately, the current generation of computational fuel cell dynamics (CFCD) models are capable of supplying such information. Future research based on CFCD and experiments will be necessary to demonstrate the benefits of convection-dominated mass-transport.

While the current model applies to single-serpentine channel geometries, many practical fuel cells employ variants of this design. For example, multi-serpentine designs have several parallel channels which make repeated 180° turns in tandem. The current model provides a framework for describing convective flow in multi-serpentine designs both qualitatively and quantitatively. Quantitatively, the quasi-1D model based on the principles of mass conservation, in-channel viscous losses, Darcy's law in the GDL, and symmetry will yield powerful analytical descriptions of convection, albeit more complicated than the current single-serpentine solution. Qualitatively, the concept of pressure drop due to viscous losses as the driving mechanism for channel bypass predicts that significant convective bypass can occur between adjacent channels with primary flows traveling in opposite directions, whereas adjacent channels with the same flow direction will experience little channel bypass. Then, multi-serpentine flow fields can be expected to have comparatively large portions of the active area which are diffusion dominated (similar to parallel channel flow fields). Again, verification of these qualitative predictions would be a convenient application of CFCD. To date, the literature has not explicitly examined the relative influence of diffusion and convection for these and other channel designs.

5. Conclusions

There are compelling reasons to believe that channel bypass can improve the performance of fuel cells such as the ability of convection to deliver higher oxygen concentrations to the catalyst layer as well as the ability to remove water vapor at lower concentrations. While not explicitly modeled here, convection may also improve the ability to move liquid water from the GDL to the channels of the bipolar plate. Experimental evidence of the positive influence of convection has been demonstrated by Williams et al. [10], and has specifically been linked to material properties of the gas diffusion layer.

The analytical model developed here admits a simple method for determining the amount and relative influence of fluid convecting into the GDL by channel bypass in single-serpentine flow fields. The model shows that the percentage of flow which travels through the GDL on any given 'pass' is directly related to the lumped non-dimensional parameter m (see Eq. (20)) which contains material and geometric parameters; this confirms the belief that the GDL and the bipolar plate are strongly coupled in determining fuel cell performance. Also, by means of the Peclet number, the relative influence of convection can be determined. It is found that GDL thickness has little affect on the relative influence of convection, while GDL in-plane permeability is crucial. In addition, convective bypass can be increased in single-serpentine flow field geometries by simply increasing the length of the flow channel. It may therefore be advantageous to employ rectangular rather than square active areas.

The principles of the single-serpentine model may also be used to give a qualitative assessment of multi-serpentine configurations. It is suggested that future research focus on the use of computational fuel cell dynamics (CFCD) incorporating reaction kinetics to determine *how much* improvement can be achieved by encouraging convection dominance.

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