Single serpentine flow fields design and sub-rib convection analysis for a PEM fuel cell

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Abstract. In a polymer electrolyte membrane fuel cell (PEMFC), transport of reactant gases through a bypass convection mechanism established between two adjacent channels along the gas diffusion layer (GDL) under the serpentine type flow field of a bipolar plate can enhance the fuel cell performance by reducing the power losses. In this paper, three different serpentine type flow field models for bipolar plates of a PEM fuel cell unit have been designed, with different channel width/rib width ratios of 1, 1.05 and 1.2, and different pressure loses have been evaluated. An analytical model for bypass sub-rib convection, based on two adjacent flow channels and a serpentine in contact with a GDL layer was used here. This model established the influence of bypass convection in the form of Peclet number $Pe$ for the flow field models, by modifying the GDL thickness $t$ (mm) and active channel length $L$ (mm). The optimal combination of thickness $t$, porosity $\varepsilon$ and permeability $k$ for a series of commercial GDL materials from the perspective of sub-rib convection was established for Sigracet$^{\mathrm{TM}}$ GDL 35 BC, with highest $Pe$ number modified along the channel.

1. Introduction

Proton exchange membrane fuel cell (PEMFC) represent at this moment one of the most attractive clean energy source from the market, working at low temperatures between 65-80$^\circ$C and having high electrical efficiencies (40% – 60%), with quick start up and rapid response to load changes, and is considered as an efficient energy system for automotive applications[1,2].

One of the most important components of the PEMFC is represented by the bipolar plate, which offer a path for a uniform distribution of reactant gases via flow channels, dissipate heat from reaction sites, prevent leakage of gases and create the electrical connection between multiple cells in a stack.

The bipolar plate flow field design generates a fundamental impact on enhanced mass transport of reactants and a proper water management. Thus, a vast number of research studies have been accomplished in order to find the optimal design for flow field that would create a high and stable cell performance. The flow field with serpentine type channels develop an efficient water removal (as the main reaction product) from the cathode, establish a moderate pressure drop along the channels and offer a good humidity inside the cathode area of the field in order to avert the electrolyte membrane dehydration[3-5].

Some numerical and experimental studies have been oriented on PEMFC channel geometry optimization, by modifying the channel width $a$, channel height $b$ and distance between two adjacent channels (rib width), $w$. The influence of channel to rib width ratio $a/w$ (varied between 0.5 and 2) on...
the PEMFC electrical performance was experimentally investigated for a serpentine-type flow field and the ratio of unity presented best performances concerning the VI/PI electrical curves [6]. For this study, the active area of the flow field was 5 cm², with MEA based of Nafion 117 electrolyte membrane. Another numerical study developed for the dimension optimization of serpentine type channel based on a genetic algorithm and also using Computational Fluid Dynamics (CFD) software Fluent (AnsysTM) for electrical performance evaluation of the PEM fuel cell offered optimal values of $a = 0.762$ mm and $w = 0.934$ mm[7].

The presence of a convective flow in the under-rib regions at bipolar plate/GDL boundary enables more effective utilization of electrocatalysts by increasing the reactant concentration and by facilitating liquid water removal in those regions [8]. Experimental studies have shown that higher gas diffusion layer (GDL) permeability improves the performance of PEMFCs with serpentine flow-fields [9] and reduces the pressure drop [10].

Starting from the reported optimal domain of $a/w$ ratio around 1 for the flow channels, three serpentine-type flow field models have been designed in this paper, with following geometrical dimensions of channel width/rib width ratio $a/w$, in mm: 0.9/0.9, 0.78/0.9 and 0.78/0.82. The inter-channel bypass convection produced at the interface between flow field channels and GDL layers was investigated with an analytical model developed by J.P. Feser et al. [11].

2. Flow fields design

Geometrical dimensions of the reactant flow fields, considered afterwards for being transferred by milling on graphite type bipolar plates of a PEMFC cell, have been established starting from the dimensions of Membrane Electrode Assembly (MEA). The MEA contains an electrolyte membrane type Nafion 117 (DuPontTM) framed inside the assembly by the catalyst layer (CL) containing Pt nanoparticle catalyst supported on carbon black (Pt/C) and by the GDL type SigracetTM 10 BC, a bilayer structure consisting of a macro-porous backing material(carbon fiber paper) and a micro-porous, carbon based layer(MPL). The active surface area of commercially available MEA was 23 x 23 mm.

For start, it was considered a first flow model for which it was established a fixed number of serpentine-type channels, with dimensions $a = w = 0.9$ mm. Channel height for all the models was considered $b = 1$ mm. By taking in consideration the MEA dimensions, it was selected the width of this flow model as $H_2 = 21$ cm, thus ensuring for both sides of the field a distance of 1 mm till the extremities of the MEA. The flow field length $H_1 = 26.1$ mm was calculated for this model M1 starting from the expression:

$$H_1 = a \cdot n_{ch} + w \cdot (n_{ch} - 1)$$  \hspace{1cm} (1)

Bi-dimensional images of the flow field model M1-M3 for the anodic bipolar plate are presented in figure 1. It can be seen here the presence of a two-channel assembly (with distance $s$ between channels) and a serpentine in the gas inlet zone which is not inside the active area of the MEA for models M2 and M3. This special configuration was considered in order to stabilize the flow at a periodic, repetitive velocity field and to provide lower and more uniform pressure drops across the following serpentes in contact with the MEA assembly. The bipolar plate at the cathode will have an identical pattern of the flow field, which is arranged in the mirror on the plate (the gas inlet to the left of the field).

For the last two flow field models we considered the same dimensions $H_1$ and $H_2$ and the same number of channels as in the case of model M1. The distance $s$ between the upper channels for models M2 and M3 was calculated starting from the relation:

$$H_1 = a \cdot n_{ch} + w \cdot (n_{ch} - 2) + s = 26.1$$ \text{mm} \hspace{1cm} (2)

Total length of the channels for flow fields M1-M3 was calculated with the following relations:
Geometrical features for the designed flow fields of bipolar plates are presented in Table 1. The designed flow fields M1-M3 were transferred on graphite plates by milling using a Computer Numerical Control (CNC) machine from the research laboratory Fuel Cell and Hydrogen Storage, 3Nano-SAE Research Center, Bucharest.

Table 1. Geometrical dimensions for flow field models with active area of 26.1 cm x 2.1 cm and channel height \( b = 1 \) mm

| Model | \( a(\text{mm}) \) | \( w(\text{mm}) \) | \( s(\text{mm}) \) | \( L(\text{cm}) \) | \( w/a \) |
|-------|------------------|------------------|------------------|------------------|---------|
| M1    | 0.9              | 0.9              | 0.9              | 34.02            | 1       |
| M2    | 0.75             | 0.9              | 3.15             | 33.96            | 1.2     |
| M3    | 0.78             | 0.82             | 3.74             | 33.95            | 1.05    |

For internal reactant streams like those specific to PEMFC bipolar channels, Reynolds number is defined as [11]:

\[
\text{Re} = \frac{\dot{m} \cdot D_h}{\mu A_c}
\]  

(5)

with characteristic scale length of the channel expressed as a function of hydraulic diameter \( D_h = 2a \cdot b/(a+b) \). In relation (5), \( \dot{m} \) is the mass flow rate (Kg/s), \( \mu \) is the air dynamic viscosity (Kg/m·s) and \( A_c = a \cdot b \) is cross-sectional area of the channel (m²).

In order to maintain the laminar flow regime inside the bipolar plate channels, the maximum Re number has to be around 2000. On the other side, in order to maintain a proper convection of the flow, the minimum Re value has to be 100[11].

The rectangular type flow channel length can be calculated starting from the Hagen – Poiseuille law[11]:

\[
L = \frac{8\Delta \rho \cdot (ab)^3}{C \mu \dot{m}(a+b)^2}
\]  

(6)

were \( C = fRe_{pb} \) represent the Poiseuille number, a constant dependent on the ratio \( a/b \).
An analytical form of the Poiseuille number for rectangular micro-channels at laminar flow, validated by experimental measurements of the $Re$ variation as a function of the friction coefficient $f$ was expressed as [12, 13]:

$$f Re_{th} = \frac{D_b}{\sqrt{A}} \left[ 1 - \frac{192}{\pi^2} \varepsilon \tanh \left( \frac{\pi}{2\varepsilon} \right) \right] \left( 1 + \varepsilon \right) \sqrt{\varepsilon}$$

(7)

were $\varepsilon = b/a$ is the channel aspect ratio.

The hydrodynamic developing region, $L_D$, depends on the aspect ratio of rectangular cross-section channels and can be obtained with expression [14]:

$$L_D = \frac{4\varepsilon}{(1 + \varepsilon)} \cdot \frac{\rho Q}{\mu}$$

(8)

were $Q$ (m$^3$/s) is the air volumetric flow rate through the channel and $\rho$ is the air density (Kg/m$^3$).

The minor pressure losses in the form of 90° channel bend pressure losses due to the presence of serpentinaes are evaluated with relation [14]:

$$\Delta P_b = \frac{\rho Q^2}{2A} \cdot K_b \left( \frac{A}{A_t} \right)^2$$

(9)

were $A$ and $A_t$ are the channel and connecting tube cross-sectional areas, respectively and $K_b$ is the loss coefficient for the bend, considered as 1.2 for a 90 degree bend[14]. We will consider here $A = A_t$, like in other studies which evaluates this type of losses [14, 15].

3. Analytical model for sub-rib convection

In figure 2 below was presented a PEMFC sub-system located at cathode, formed by two channels and a serpentine from the bipolar plate flow field, in direct contact with GDL layer. The main purpose is to evaluate the inter-channel bypass convection established through GDL along under-rib regions, delimited by channel section with length $L_{ch}$. During parametric calculations, the geometric features for the channels have been modified in accordance with M1-M3 model dimensions from Table 1. The active channel length $L_{ch}$ will vary from one model to another under the form $L_{ch} = H_2 - 2a$, with the following values: 19.2 mm, 19.4 mm and 19.44 mm.

The sub-rib convection model considered here [11] uses two main assumptions that greatly simplify the analysis: density and viscosity of air in the gas channel remains constant during the fuel cell operation and the magnitude of the secondary velocities, $v$ and $w$ are much smaller that the velocity along the direction of the channel, $u$.

![Sub-rib convection model for evaluating the flow performances of models M1-M3](image)

Figure 2. Sub-rib convection model for evaluating the flow performances of models M1-M3
One key parameter used here to evaluate qualitatively the flow enhancement of the reactant gas circulating along the GDL through bypass convection is the non-dimensional convection coefficient \( m \) [24]:

\[
m = \frac{2L_{ch}}{A} \frac{t \cdot k}{b \cdot f}
\]

In relation (10), \( t \) represent the GDL thickness, with value of 0.42 mm and GDL permeability \( k = 2.2 \times 10^{-11} \text{ m}^2 \) for Sigracet™ GDL 10 BC. The non-dimensional coefficient \( f \) from the relation above is dependent on the channel geometrical features and has a value of 0.035 due to a ratio \( b/a \) close to 1 for all the flow field models [11].

A particular quantity of interest is the amount of flow which penetrates into GDL along the extremity of the serpentine, expressed as a ratio of flow going around the corner to the total flow of air:

\[
\frac{Q_{\text{corner}}}{Q_{\text{total}}} = \frac{2}{m \cdot \tanh(m/2) + 2}
\]

So, the proper selection of the dimensionless parameter \( m \) can increase the percentage of flow travelling under the lands. In order to compare the relative influence of convection versus diffusion, the present analytical model defined the Peclet number \( Pe \) in such a manner to show the importance of convection underneath the lands (areas between channels) in the plane direction, being calculated with expression [11]:

\[
Re = \frac{2M_{\text{air}} \cdot N_c L_{ch} (w + a) a}{4F \gamma_{O_2} \mu A_c} \left( \frac{2}{m \tan(m/2) + 2} \right)
\]

In the relation above we considered \( N_c = 14 \), molar mass of air \( M_{\text{air}} = 0.078 \text{ Kg/mol} \), Faraday constant \( F = 96485.33 \text{ C/mol} \) and molar fraction of oxygen in air: \( \gamma_{O_2} = 0.21 \).

4. Results and discussions

The pressure drop along the entire serpentine type channel system, with length \( L \) (see Table 1) was evaluated for flow field models M1-M3 with expression:

\[
\Delta p = \frac{L \cdot f \ Re_{ch} \cdot \mu \cdot m \cdot (a + b)^2}{8 \cdot \rho \cdot (ab)^3}
\]
were $fRe_{Dn}$ represent the Poiseuille number, calculated with relation (7). In expression (14), dynamic viscosity and density for air at 80°C were: $\mu = 2.088 \times 10^{-5}$ Pa·s and $\rho = 1$ Kg/m$^3$.

Experimental investigations of PEMFC unit cell, published elsewhere [16] have been performed at two different air volumetric flow rates: $Q_1 = 1 \times 10^{-5}$ m$^3$/s and $Q_2 = 1.33 \times 10^{-5}$ m$^3$/s, which will be used also in the present parametric flow calculations. The equivalent mass flow rates were $\dot{m}_1 = 1.076 \times 10^{-5}$ Kg/s and $\dot{m}_2 = 1.722 \times 10^{-5}$ Kg/s.

With the above $\dot{m}$ and $Q$ values, the following parameters have been evaluated for flow field models M1-M3: $Re_{Dh}$ with relation (5), $L_D$ with relation (8) and 90° bend pressure losses $\Delta P_b$ with expression (9); after that, the calculated parameters have been tabulated in Table 2.

**Table 2. Specific parameters for flow field models M1-M3**

| Models | $Re_{Dh}$ | $Re_{Dh,1}$ | $Re_{Dh,2}$ | $L_{D1}$ (mm) | $L_{D2}$ (mm) | $\Delta P_1$ (kPa) | $\Delta P_2$ (kPa) | $\Delta P_{b1}$ (Pa) | $\Delta P_{b2}$ (Pa) |
|--------|-----------|-------------|-------------|---------------|---------------|---------------------|---------------------|---------------------|---------------------|
| M1     | 399.31    | 572.58      | 916.34      | 1.72          | 4.57          | 26.04               | 41.67               | 93.33               | 124.1               |
| M2     | 433.56    | 624.63      | 999.65      | 1.43          | 3.81          | 41.48               | 66.38               | 112                 | 148.9               |
| M3     | 426.25    | 644.15      | 1030.9      | 1.49          | 3.96          | 37.45               | 59.93               | 107.7               | 143.2               |

The main bypass sub-rib convection parameters have been evaluated with expressions (10) – (13) and introduced in Table 3. We could observe from here that the model M3, with highest convection coefficient $m$ (but very close to that of the model M2) showed the highest percentage value of air flux circulating along GDL at serpentine boundaries, and thus contributing in the highest degree at bypass inter-channel convection.

**Table 3. Parameters calculated through the analytical model of sub-rib convection for flow fields M1 – M3**

| Parameters          | Flow field models |
|---------------------|-------------------|
|                     | M1                | M2                | M3                |
| $m$                 | 0.731             | 0.890             | 0.894             |
| $Q_{corner}/Q_{total}$ | 0.886             | 0.843             | 0.842             |
| % GDL flux flow     | 11.34             | 15.67             | 15.78             |
| $Re$                | 347.9             | 252.1             | 287.5             |

The analytical model described above was validated by comparing with a FEM numerical model of a two-channel assembly and a serpentine identical to that presented in figure 2, but considering transport by convection at a three-dimensional level. This numerical model, described in detail in a previous work provides the interaction between GDL and flow channels through the Navier-Stokes equations for incompressible flow in the channels and the Brinkman extension of Darcy’s law with the Forchheimer correction for gas diffusion through GDL. It should be mentioned here that the analytical model considers a slow velocity variation along the $x$ direction and a slow variation of the pressure across the $z$ direction so that the Navier-Stokes equation has been reduced to a one-dimensional form. In conformity with the analytical model, the pressure variation along the active channel length $L_{ch}$ will verify the equation [11]:

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

(15)

were pressure drop along the entire flow fields of the bipolar plates inside the PEMFC unit cell was evaluated as:
\[
\Delta P_{cell} = P_{inlet} - \Delta P_{loss}
\]  

(16)

In above expression, \(P_{inlet}\) was taken as the inlet pressure of reactant air at cathode during experimental testing, being equal with 200 kPa [16]. For validation it was considered model M1 with \(\Delta P_{loss} = 26.042\) kPa (see Table 2) and \(N_c = 14\). As we can see in figure 3, the pressure variation for model M1 in conformity with relation (16) has been overlapped with the evolution of local pressure across the inner boundary of the flow channel in contact with GDL layer, along the same length \(L_{ch} = 19.2\) mm, as it resulted from the 3D numeric simulation. We can see here a good match between the analytical model solution and the numerical model.

We will further evaluate the effect of modifying the active channel length \(L_{ch}\) for mass transport of reactants through convection as well as some specific GDL parameters, like thickness \(t\), permeability \(k\) and porosity \(\varepsilon\) on the Peclet number \(Pe\).

**Figure 3.** Comparative study between the pressure drop along the active channel length \(L_{ch}\) for analytical model and a numerical 3D model

Starting from relation (11), it was evaluated the variation of Peclet number along the active channel length \(L_{ch}\) for all the flow field models, as we can see in fig. 4.a. Model M3 presented the highest values of \(Pe\) along entire \(L_{ch}\) length, being 0.665 at 0 mm and 0.323 at 10 mm.

**Figure 4.** (a) \(Pe\) variation along the active channel length for M1-M3 models (\(t = 0.42\) mm) and (b) \(Pe\) evolution by modifying GDL thickness for model M3
It was studied next the effect of modifying the GDL thickness $t$ (mm) on the Peclet number $Pe$ for the model M3 with highest inter-channel convection, as we can see in fig. 4.b. Only a few percent increases in $Pe$ number was observed at a decrease in the GDL thickness from 0.42 to 0.1 mm, indicating that the inter-channel convection phenomenon is practically insensitive to the change in the diffusion layer thickness.

Figure 5.a. presents the variation of $Pe$ for common domains of channel lengths $L_{ch}$ in the case of M3 flow pattern. By increasing the length $L_{ch}$ of the flow channel it was found, a significant increase of $Pe$ could be observed. We noticed also here the appearance of a curvature in the $Pe$ profile variation at $L_{ch} = 40$ mm and $L_{ch} = 50$ mm, lengths for which the convection coefficient $m = 1.88$ and $m = 2.35$. This bending was occurring as a result of a slight reduction of the air flow velocity in the center of the channel, phenomenon produced when $m$ approaches or exceeds the value of 2 [11].

Finally, we considered a series of commercial GDL materials characterized by different values of parameters $t$, $\varepsilon$ and $k$ (see Table 4) for which was evaluated the influence of inter-channel convection in the form of $Pe$, considering the optimized M3 model for bipolar plate in contact with GDL. The products of four types of GDL manufacturers: TGP-H-030 created by Toray Industries (Japan), Sigract GDL produced by SGL Group (Germany), ELAT LT 1200W produced by ETEK Company (USA) and H2315 I2 C6 produced by Freudenberg Group (Germany) have been considered for performance evaluation.

**Table 4.** Properties of some commercial GDL materials

| Material     | $t$ (mm) | $\varepsilon$ | $k_{GDL}$ (m$^2$) | Reference |
|--------------|----------|---------------|-------------------|-----------|
| GDL 10 BC    | 0.42     | 0.82          | 2.2 x 10$^{-11}$  | [18]      |
| GDL 35 BC    | 0.325    | 0.52          | 1.72 x 10$^{-11}$ | [19]      |
| GDL 24 BA    | 0.190    | 0.74          | 3.67 x 10$^{-11}$ | [19]      |
| GDL 35 BA    | 0.30     | 0.70          | 5.31 x 10$^{-11}$ | [19]      |
| LT 1200W     | 0.275    | 0.32          | 4.98 x 10$^{-12}$ | [19]      |
| H2315 I2 C6  | 0.25     | 0.46          | 8.57 x 10$^{-13}$ | [19]      |
| TGP-H-030    | 0.11     | 0.64          | 2.2 x 10$^{-11}$  | [19]      |

It can be seen in figure 5.b that the analytical model having GDL type H2315 I2 C6 showed a $Pe$ evolution very close to 0 across the entire channel length considered, suggesting the exclusive existence of the binary diffusion transport mechanism for this model. It should be noted that the GDL 35 BC flow pattern with a coefficient $m = 0.695$, lower than recorded in the case of GDL 10 BC model ($m = 0.894$) presented $Pe$ values significantly improved.

**Figure 5.** a) $Pe$ evolution at different active channel lengths and b) $Pe$ variation along the nominal channel length for various commercial GDL materials
5. Conclusions
The serpentine-type flow field model M3 presented intermediate pressure drop across the channels and highest Reynolds numbers at two different mass flow rates, with about 16% bypass convective flow through GDL, around the corner of the serpentines in the flow field. The rest of 84% from the total air flow was associated with the binary diffusion mechanism. Peclet number $Pe$ for model M3 was with about 8% higher by comparing with model M2 along the first half of the active channel length $L_{ch}$.

Peclet number insensitivity to GDL thickness variation, observed in the present analytical calculations can have important implications for PEM fuel cell development since the thickness reduction of diffusion layer can reduce the material cost, stack volume and over-potential losses.

The optimal combination of values for the three functional parameters involved in bypass convection mechanism: $t$, $k$ and $\varepsilon$ was identified for the GDL 35 BA material of the M3 flow field model, which also had the highest convection coefficient $m = 1.17$.

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