Modeling and simulation of novel modified single-serpentine flow-field design in bipolar plates for Direct Ethanol Fuel Cells

W. J. Pech-Rodríguez[1], D. González-Quijano[1], J.I. Escalante-García[1], G. Vargas-Gutiérrez[1], F.J. Rodríguez-Varela[1,*]

[1]CINVESTAV-IPN, Unidad Saltillo,
Av. Industria Metalúrgica 1062. Ramos Arizpe, Coahuila, C.P. 25900, México.
[*]Tel: (844) 438-9600 ext 8526, mail: javier.varela@cinvestav.edu.mx

ABSTRACT

This paper presents the design and modeling of a novel modified single-serpentine flow field design, proposed to enhance the flow of ethanol in the anode bipolar plate of a Direct Ethanol Fuel Cell (DEFC). A three-dimensional flow-field model is simulated by computational fluid dynamics (CFD) with the aid of the Comsol software, to emulate the liquid velocity distribution along an 8-parallel channels bipolar plate. The comparison between the novel design and the conventional serpentine flow-field reveals that the reduction of the cross sectional area leads to a higher liquid velocity and a more homogeneous velocity distribution along the flow channels. Such enhancement in distribution is directly related to a better mass transfer of ethanol from the flow channels to the electrode, improving the performance of the fuel cell. Consequently, their use in DEFCs can lead to higher fuel cell efficiencies.

1. Introduction

In the past few decades, the use of alcohols in direct alcohol fuel cell (DAFC) has been extensively studied as power sources for electric vehicles and for both stationary and portable applications [1]. Compared with hydrogen fed polymer electrolyte fuel cell (PEMFCs) they offer some advantages. They use liquids as fuel (i.e., their production, storage and distribution are simple), and their theoretical mass energy density is rather high [2, 3].
Despite these advantages, the DAFCs show lower efficiencies than PEMFCs, due to slow oxidation kinetics of fuel alcohols and the fuel crossover through the membrane from the anode to the cathode side [4]. To circumvent these problems, intense studies have been carried out for evaluating and optimizing the anode compartment.
Several investigations have been carried out on the design and modeling of anode flow fields of DAFCs and their influence on their electrochemical performance. Various types of channel configuration have been used for fuel flow field in the bipolar plate. Arico et al. [5] investigated the effects of serpentine and interdigitated flow fields on the DMFC performance. Their experimental results showed that the power densities are influenced by the channel configuration. Miaomiao proposed the use of non-equipotent serpentine flow field to remove the CO_2 bubbles from a micro Direct Methanol fuel Cell (μDMFC), leading to a significant promotion of the μDMFC performance [6]. Computational fluid dynamics (CFD) techniques have been used to study the flow and mass transport phenomena in fuel cells, reducing the costs of bipolar plates production and optimizing mass transport [4].
In this work, we investigated the effect of the single serpentine and modified single serpentine in the velocity distribution, pressure drop and Reynolds number of a DEFC flow channel.

2. Methodology

We used three dimensional computational simulation to investigate ethanol flow, pressure drop, and velocity gradient in two different flow field design. The modeling and simulation were performed by using Comsol Multiphysics 4.3a. The numerical model is steady state and the flow distribution was described by Navier-Stokes and continuity equations.

The base channel geometry for flow field used in this work was a simple serpentine flow field. One prototype is the Simple Serpentine Flow Field (SSFF) having 0.6 mm width and 0.4 mm deep channels and 0.6 mm ribs. This model was composed by 7 channels and 6 ribs. The behavior of the SSFF was compared to the second prototype, i.e., the Modified Serpentine Flow Field (MSFF) having the channel width gradually changing along the channel length. The MSFF had 0.4 mm deep channels and 0.6 mm ribs.Figure 1 shows the SSFF (fig. 1a) and MSFF (fig. 1b) flow fields, each with a total length of 59.5 mm.

A comparison of the behavior of the SSFF and MSFF flow channels in the fuel comportment was performed on the basis of the same channel depth. The open ratio (the ratio of the channel area or the exposed portion of the membrane electrode assembly, MEA) for SSFF and MSFF were 56 and 50%, respectively. The experiments were carried out by keeping the inlet at atmospheric pressure, room temperature and the fuel flow rate at 1 mL min^{-1}. An ethanol concentration of 1M was considered for the experiments. The boundary conditions were slip (zero flux) for the walls and others such as inlet and outlet of the flow channels. The model used pressure/no viscous stress boundary conditions for inlet and laminar outflow for outlet. The solver used Direct Umpack method with a mesh of 386629 and 367913 degrees of freedom for SSFF and MSFF, respectively. The computation time to resolve the geometry was around 10 minutes on a 2.5GHz and 6 GRAM PC. The result of drop pressure, velocity fields and Reynolds number was evaluated.

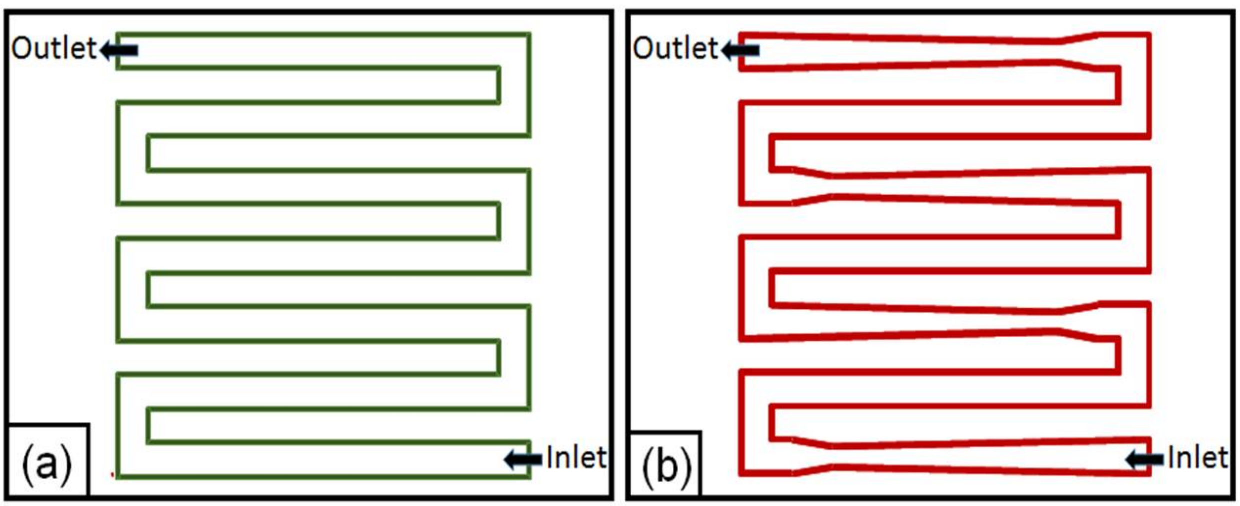

Figure 1 Designs of the anode flow field: a) Serpentine flow field, SSFF; b) Modified serpentine flow field, MSFF.

In this study, the flow of ethanol in the anode compartment was evaluated by the Reynolds number defined as [5, 7]:

$$Re = \frac{\rho Q_{in} D}{\mu A} \tag{1}$$

where Q_{in} is the ethanol solution flow rate at the inlet of flow channel, D is the hydraulic diameter, and A the cross section area of flow channels. The Reynolds number was useful to characterize the flow regimes in the liquid flow channel of DEFC.

3. Results and discussions

The specifications of the two prototype flow channels are summarized in table 1. From this data it can be observed that in both prototypes the Reynolds number is lower than 2100, indicanding that the fuels has a laminar flow in the channels.

Table 1 Geometry of the flow field

Flow Field	Channel depth/mm	Channel lenght/mm	Rib width/mm	Open ratio/%	Re
SSFF	0.4	60	0.6	56	4.7
MSFF	0.4	60	0.6	50	5.3

Figure 2 and 3 show pressure drop through the flow field channel (flow of fuel: 1 mL min^{-1}). The pressure drop for SSFF is 552 Pa. Meanwhile, the pressure drop for MSFF is 716 Pa. The pressure difference between the SSFF and MSFF flow channels is 164 Pa. This difference in pressure drop is due to the gradual change along the channel length of MSFF, which results in decrement in its cross section area.

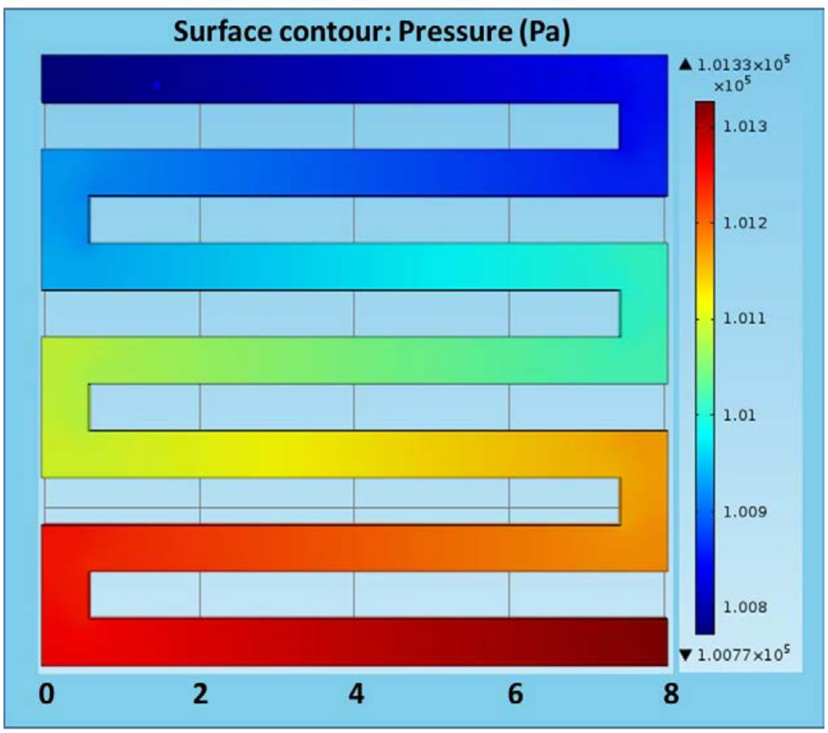

Figure 2. Contour of pressure distribution of SSFF

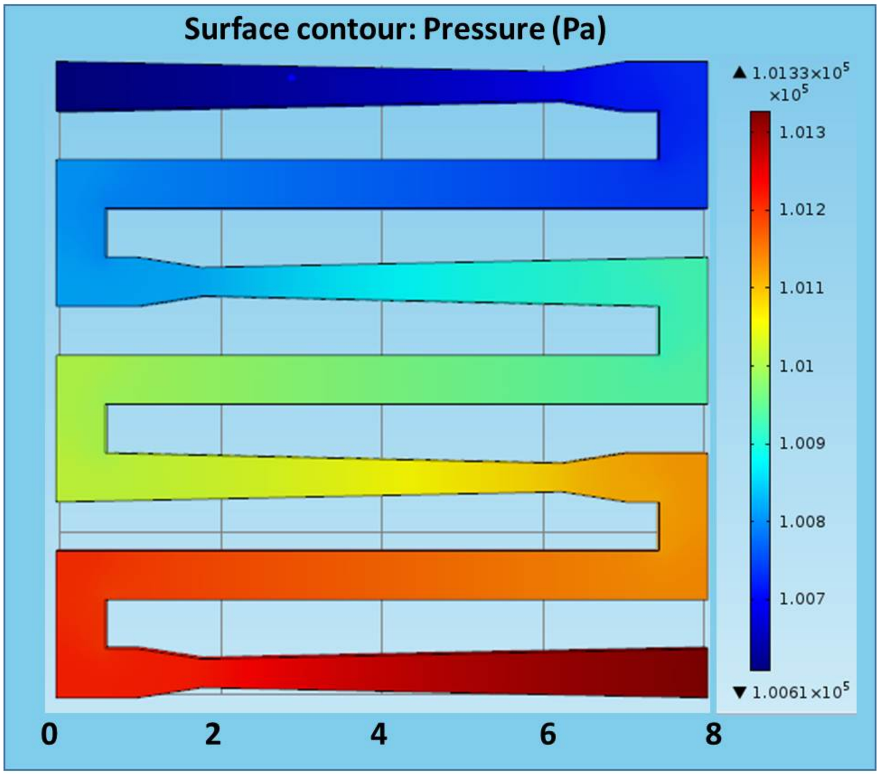

Figure 3. Contour of pressure distribution of MSFF

Figure 4 and 5 show the velocity distribution along the channels of SSFF and MSFF, respectively. In the case of SSFF, the maximum velocity is 0.14 m s^{-1} and the minimum is 0.132 m s^{-1} with one average of 0.1342 m s^{-1}. Meanwhile, for MSFF the highest velocity is 0.19 m s^{-1} and the lowest value is 0.131 with one average value of 0.1601 m s^{-1}. The velocity difference between the SSFF and MSFF is about 19.2%. This difference in the average ethanol velocity can attributed to the change in cross sectional area of the MSFF flow channel. The velocity inside the channel is given as:

$$u = \frac{Q_{in}}{A} \qquad (2)$$

where u is fluid velocity, Q_{in} is the volumetric flow rate (1mL min^{-1}) and A is the cross sectional area of the channel. It is known that the diffusion is the predominant mechanism of mass transport in the porous diffusion, although it has been recognized recently that convection in the porous diffusion layer is significant when serpentine flow fields are adopted [8]. One way for evaluated the ratio of convective to diffusive mass transport is determining the Peclet number, this number can be calculated according to the relationship:

$$Pe_x = u.\frac{L}{D} \tag{3}$$

where D is mass diffusivity and L is the characteristic length.

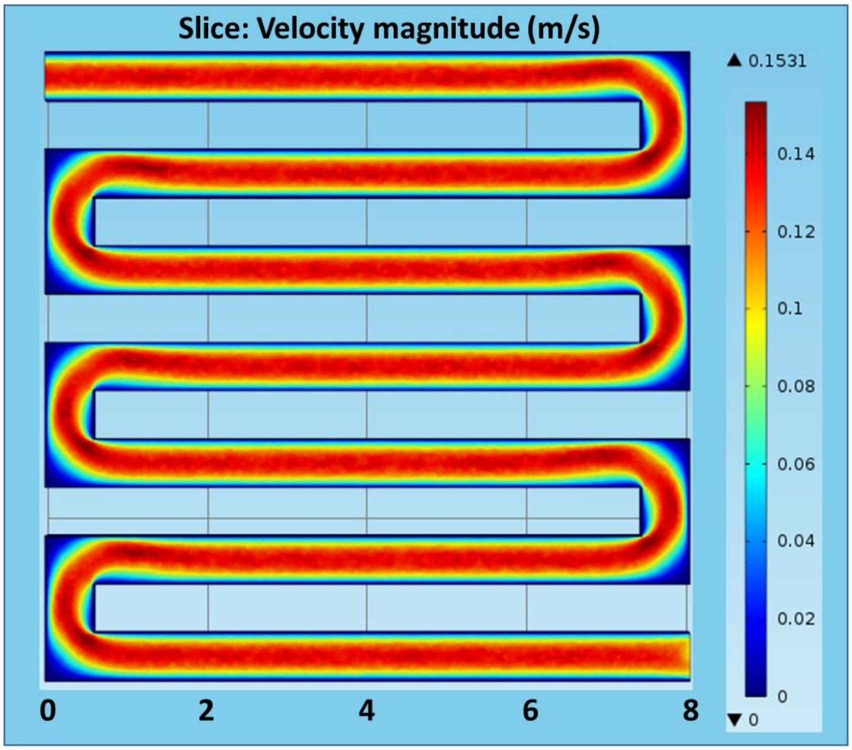

Figure 4 Contour of velocity distribution in Simple Serpentine flow field

The mass transfer coefficient of ethanol from to the flow field to the gas diffusion layer is given by the Sherwood number, and it can be written as [9]:

$$Sh_X = Pe_x \int_0^{\frac{H_x}{L}} \frac{\partial C}{\partial X} dY \tag{4}$$

Where C is the ethanol concentration, Hx upper boundary region and L is the characteristic length. From equation 4 we can see that Sh_X increase with an increase in the local Peclet number. Therefore, a decrement in the cross sectional area give an increase in Sherwood number, enhancing the mass transport of ethanol to the catalysis layer.

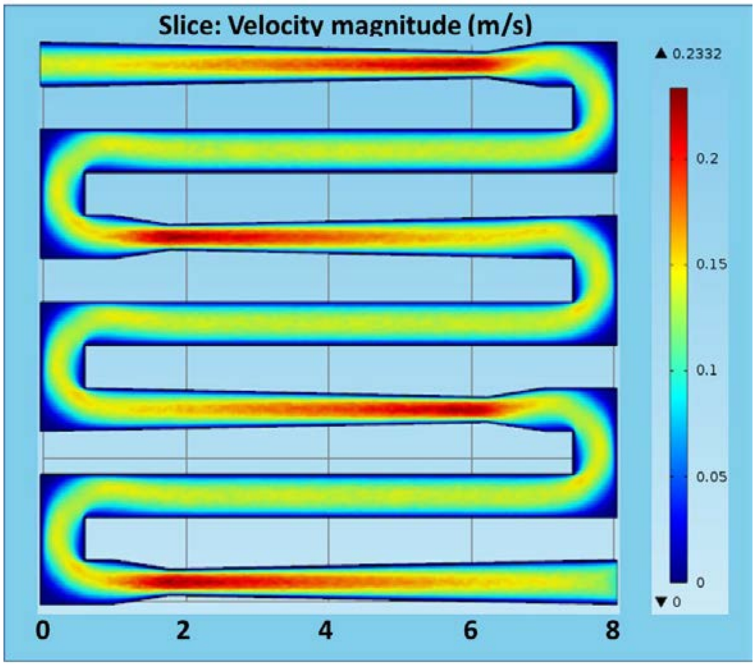

Figure 5 Contour of velocity distribution in Modified Serpentine flow field

4. Conclusions

We conducted CFD analysis to study properties such as Reynolds number, pressure drop and velocity distribution for liquid ethanol along two different flow channels configurations: SSFF and MSFF. The results showed that the MSFF has higher velocities compared to SSFF. The highest velocities increased the Peclet number and the Sherwood number. Therefore, the mass transfer coefficient of ethanol from to the flow field to the gas diffusion layer was considered to be high and may produce better performance in DEFC. On the other hand, the high velocities of ethanol in DEFC can enhance the pressure gradient at high current densities, because these operations conditions help to remove CO_2 bubbles accumulated along the channels.

5. Acknowledgments

The authors wish to thank Conacyt for financial support through grant 164251.

6. References

[1] Sen Gupta, S. and J. Datta. J. Chemical Sciences, 117, 4 (2005).
[2] Fabrice Vigier, Séverine Rousseau, Christophe Coutanceau, Jean-Michel Leger, and Claude Lamy. Topics in Catalysis, 40 1-4 (2006).
[3] S. Rousseau, C. Coutanceau, C. Lamy, J.-M. Léger. J. Power Sources, 158, 1 (2006).
[4] U. Krewer, Y. Song, K. Sundmacher, V. Johnb, R. Lubkeb, G. Matthies, L. Tobiska. Chemical Engineering Science, 59, 1 (2004).
[5] Yang, H. and T.S. Zhao. Electrochimica Acta, 50, 16-17 (2005).
[6] Miaomiao Li，Junsheng Liang，Chong Liu, Gongquan Sun and Gang Zhao. Sensors, 9, 5 (2009).
[7] Griskey, R.G., h, Transport Phenomena and Unit Operations: A Combine D Approach, 1 ed. John Wiley & Sons Australia, 2003.
[8] Ye, Q., T.S. Zhao, and C. Xu. Electrochimica Acta, 51, 25 (2006).
[9] Yang, H., T.S. Zhao, and Q. Ye. Electrochemistry Communications, 6, 11 (2004).