Experimental and Numerical Study of Concentration, Flow and Temperature Fields in a Fuel Cell Model Channel

J. C. Torchia-Núñez*[1] & J.G. Cervantes-de-Gortari[1]
[1] Department of Thermal Engineering, National University of Mexico, UNAM
*Corresponding author: Laboratorio de Termofluidos, Anexo de Ingeniería, Ciudad Universitaria, UNAM, tadeo_isidoro_cruz@yahoo.com

Abstract: Flow, concentration and temperature fields are studied with numerical and experimental methods inside a scaled-up fuel cell anode channel model. The low aspect ratio channel has a porous medium as the inferior wall where a mixing of different pH solutions occurs. Chromatic change of phenolphthalein is used to visualize concentration field and PIV is used to visualize the flow field.
.

Keywords: fuel cells, modeling, transport phenomena, experimental techniques

1. Introduction

Fuel cells are devices that generate electricity after an electrochemical reaction. Several phenomena are associated to this reaction, such as mass, heat and momentum transport. These three transport methods are coupled in order to produce an electrical current. This electrical current is used to feed devices ranging from cell phones to large vehicles.

Although fuel cells are already commercially available, there are several technology issues to be solved. There is an increasing body of work in fuel cells research with several approaches. However, it is the opinion of the authors that there is a lack of research regarding heat, mass and momentum transport, especially experimental research which tends to be expensive and time consuming. Fuel cells allow challenging interdisciplinary studies due to the fact that coupled and complex transport phenomena occur within a small space. One of the problems of measuring variables of phenomena within a fuel cell is the reduced geometrical scale.

In this study, a proposal of experimental and numerical methods is discussed. The experimental methods are based on optical phenomena. PIV (Particle Image Velocimetry) is performed to visualize the flow field. Concentration field is detected using a color change of a pH indicator such as phenolphthalein in an alkaline medium.

Numerical simulations are perfomed using COMSOL Multiphysics. The commercial software allows fast and reliable numerical simulations of variables related to the differential equations that describe transport phenomena.

2. Comsol Multiphysics model

Fuel cell modeling has been studied extensively under different approaches [1,3,4,5,]

The region under study is a 2-D channel whose length is 1 meter and 3 cm tall (low aspect ratio) as seen in Figure 1. Inside the channel a flow of water is driven by a pressure difference equal to 1e-4. The inferior wall of the channel is a porous medium with determinate porosity and permeability. Tortuosity and grain size are not taken into account. A 200 W/m^2 heat flux is transported from the lower boundary of the porous medium into the channel. Also, at this boundary, there is high concentration and at the inlet, concentration of species is zero. Bouyancy effects are considered.

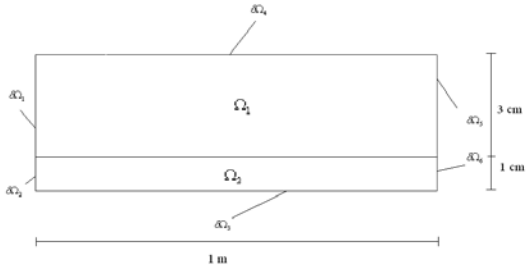

Figure 1. Subdomains and boundaries of the numerical system

The mesh is chosen as finer and the maximum size of elements in boundaries is 1e-2. Time dependent solver was used to smooth

unstabilities. Processing time was around 10 minutes every run.

Heat Tranfer and Chemical Engineering Application Modes were used to make simulations in COMSOL MUltiphysics.

Table 1: Subdomains and boundaries for the numerical system

Ω_1	Fluid channel
Ω_2	Porous medium
$\delta\Omega_1$	Inlet of channel
$\delta\Omega_2$	Insulated wall
$\delta\Omega_3$	Constant heat & mass wall
$\delta\Omega_4$	Insulated wall
$\delta\Omega_5$	Outlet of channel
$\delta\Omega_6$	Insulated wall

3. Numerical simulations

Figure 2 shows the temperature field inside the channel and the porous medium. It is seen that, when a constant heat flux is imposed, temperature varies along the longitudinal direction. Also, temperature gradient along the channel is almost zero meanwhile temperature gradients along the transversal direction is relatively large; however, the highest temperature difference is 6 °C.

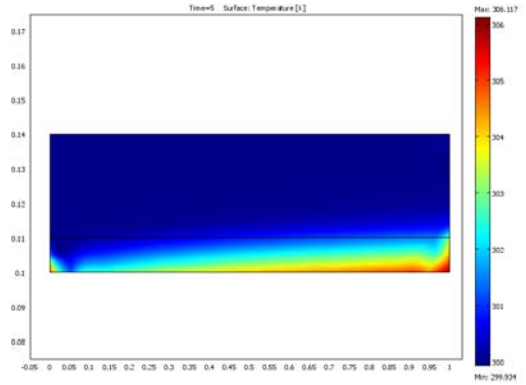

Figure 2. Temperature field of a channel model. Q = 200 W/m^2

It is not detectable the influence of natural convection due to the vertical body force under these conditions. The process of heat transport is dominated by diffusion and almost entirely within the porous medium.

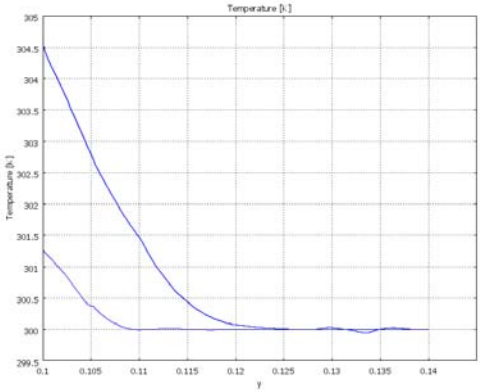

Figure 3. Temperature profile of a channel for two transversal positions, at the entrance (x= 0.05 m) and at the end of the channel (x = 0.95)

The thermal boundary layer profile is shown in figure 3. There is a detectable change between temperatures along the axial direction; this is due to diffusion process.

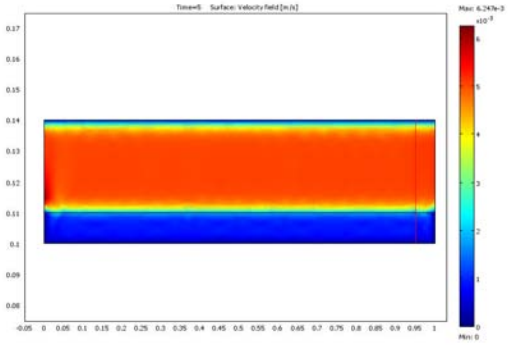

Figure 4. Velocity field of a channel.

The velocity field is shown in figure 4. The porous medium has a very low permeability, therefore, resistance is too high for the bulk of the fluid to penetrate.

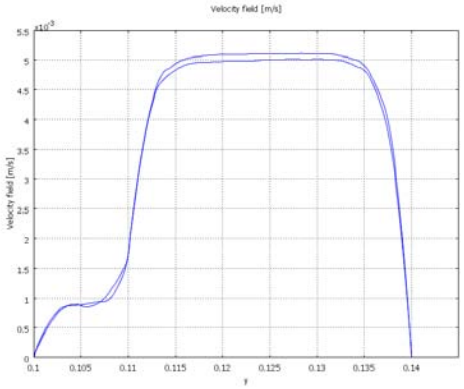

Figure 5. Velocity profile across height of the channel for x = 0.05 m and x = 0.95 meters.

The velocity profile across the transversal direction is shown in figure 5. A small velocity distribution is detected in the porous medium whereas a flat-pointed profile is almost unchanged along the longitudinal direction. There seems to be no appreciable velocity profile distortion due to the temperature field, buoyancy and heat flux.

Figure 6 shows the concentration field within the region of the channel. It has the exact form of temperature field due to the same boundary conditions and Navier-Stokes description of the flow. Although the flow is slow, diffusion processes do not seem to affect the channel due to the low transport coefficients of the substance used.

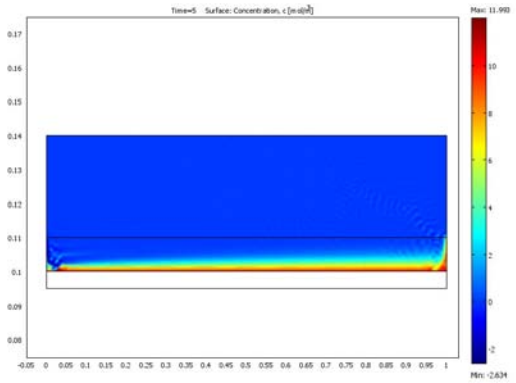

Figure 6. Concentration field in the channel

4. Experimental set-up

A channel is built with acrylic walls for optical accessibility. The lower inferior wall of the channel is a porous medium. A system is forces a pressure driven volume of water through the axial direction of the channel. The porous medium is a non-homogenous brick with a 1 cm thickness. For PIV technique, the water introduced is seeded with 10 micrometer diameter polyamide. A laser plane is formed and is passed through the channel axial-wise. The light reflected from the polyamide particles is detected with a digital camera. Velocity vectors are obtained after a cross-correlation is performed on two digital images [2,7]. An example of PIV set-up is seen on Figure 7.

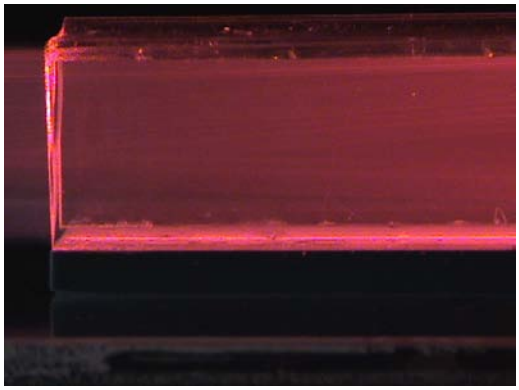

Figure 7. PIV technique on an acrylic channel using kerosene as the reflecting particle.

The experimental technique for concentration is an adaption of an acid-base color method [7]. Phenolphthalein dissolved in alcohol is introduced in the channel with water. At the base of the porous medium, a solution of hydroxide sodium is placed. As water permeates through the brick, phenolphthalein turns violet due to a chemical reaction. The amount of violet in the channel indicates the amount of ions hydroxyl, which is a measure of concentration.

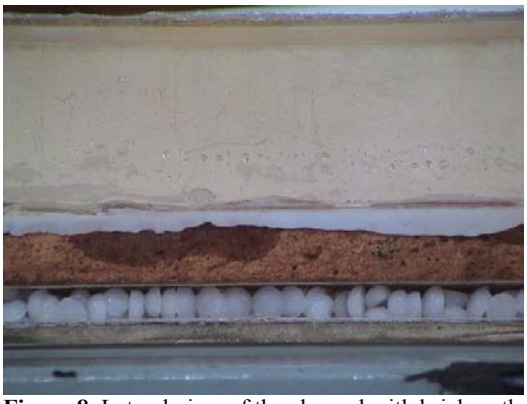

Figure 8. Lateral view of the channel with brick as the porous medium.

A very basic set-up is seen in Figure 8. The inferior wall of the channel is a 1-cm thick brick. Below the brick there is a layer of sodium hydroxide. Notice the wet (dark) spot in the brick indicating the permeation of fluid towards the “catalytic” layer. Penetration takes some time and is a function of pressure difference between inlet and outlet boundaries of the channel.

Figure 9. Phenolphthalein color change to violet in the sodium hydroxide layer.

After some time, the fluid will filter down to the sodium hydroxide layer and produce the phenolphthalein reaction:

$$\underbrace{H_2P}_{colorless} + 2OH^- \rightarrow \underbrace{P^{2-}}_{violet} + H_2O \qquad (1)$$

Notice that even then, there is no appreciable violet color in the channel. This indicates that effects on the channel take some time to manifest in the region where measurements can be performed. Also, this particular experimental set-up makes difficult to study the steady state, due to the fact that hydroxide sodium in solid state would have to be removed continuously.

5. Conclusions

COMSOL Multiphysics shows itself to be an extremely useful tool for the simulation of concentration, flow and temperature fields within a channel that models a fuel cell channel. Experimental optical methods for visualization of transport phenomena can be easily use for validation and related to COMSOL simulations. COMSOL is a versatile tool for users that need to model complex phenomena in an easy and reliable way to produce results fast enough for analysis and interpretation.

The present study is basically a discussion of some numerical simulations and experimental methods for measuring hard-to-see variables within the channel and variable profiles.

6. References

1. S.B. Beale, Calculation procedure for mass transfer in fuel cells, *Journal of Power Sources* **128,** 185–192 (2004)

2. J. P. Feser, A. K. Prasad and S. G. Advani, Particle Image Velocimetry Measurements in a Model Proton Exchange Membrane Fuel Cell, *Journal of Fuel Cell Science and Technology*, **4**, 328-335, (2007)

3. R.J. Cooper, J. Billingham and A.C. King, Flow and reaction in solid oxide fuel cells, *J. Fluid Mech.*, **411**, 233-262, (2000)

4. F.A. Coutelieris, S.L. Douvartzides and P.E. Tsiakaras, Heat transfer phenomena in a solid oxide fuel cell: An analytical approach, *Chem. Eng. Sc.*, **60**, 4423-4430 (2005)

5. H. Ju, H. Meng and CY. Wang, A single-phase non-isothermal model for PEM fuel cells, *Int. Heat & Mass Transf.*, **48**, 1303-1315 (2005)

6. J. Westerweel, Fundamentals of digital particle image velocimetry, *Meas. Sci. Technol.*, **8**, 1379-1392 (1997).

7. F. Cabaret, S. Bonnot, L. Fradett and P. A. Tanguy, Mixing time analysis using colorimetric methods and image processing, *Ind. Eng. Chem. Res.*, **47**, 5032-5042 (2007)

7. Acknowledgements

This investigation was partially supported by DGAPA-UNAM grants IN103106, IN101808 and PE101007. The first author received financial support from DGP-UNAM.

8. Appendix

Table 2: Parameters used in this study

Parameters	Value
density	1e3
viscosity	1e-3
diffusivity	4.68e-9 mol/s
Pressure difference	1e-5 Pa
Initial pressure	0.77e5 Pa
Initial temperature	300 K
Thermal capacity	4184 J/kgK
Expansion coefficient	1e-6 1/K
permeability	1e-7 m^2
porosity	0.5
Heat flux	200 W/m²
concentration	0.04 mol/m³