

Experimental Investigation of Channel Aspect Ratio on Interdigitated PEMFC Performance

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ABSTRACT

Novel water management and reactant distribution strategies are critical to next generation polymer electrolyte membrane fuel cell systems (PEMFCs). Improving these strategies in PEMFCs leads to higher power density and reduced stack size for vehicle applications, which reduces weight and improves the price competitiveness of these systems.

Interdigitated flow fields induce convective transport (cross flow) through the porous GDL between adjacent channels and are superior at water removal beneath land areas, which can lead to higher cell performance. However, the head loss due to flow, among other factors, may cause cross flow maldistribution of reactants down the channel. Such maldistribution may lead to areas of low or areas of excess cross flow. This, in turn, can cause areas of low oxygen concentration and water build up, and therefore higher pressure losses and uneven membrane hydration, all of which reduce overall cell performance. This research seeks to examine the affect varying channel dimensions have on cross flow and water distribution in an interdigitated flow field.

A modeling study of a PEMFC at various aspect ratios and flow rates was completed using the multiphysics package COMSOL. Interdigitated flow fields at varying lengths and conditions were simulated in 3D. Power and cross flow trends were the main focus of the work. Reaction by-product water is a factor; however, no models can currently account for this completely. The cross flow and current distribution was shown to be more variable in the 25 cm cell than in the 5 cm cell. The central region of the 25 cm cell, where the cross flow rate is lowest, may be subject to reduced oxygen concentration and increased water buildup. Regions toward the entrance and exit, while receiving higher cross flow rates, may be oversupplied and contributing to increased pressure drop due to higher velocities.

For experimental validation, a PEMFC was designed that could be configured to run under varying interdigitated channel length configurations through the use of separate manifold exit ports. The lengths studied were 5 cm, 15 cm and 25 cm. The flow field is comprised of 10 channels with width/depth/land dimensions all of 1 mm. To isolate the effect of the cathode interdigitated flow field, the anode was run in parallel. Polarization and inlet pressure curves were produced for each length case at two different stoichiometries. Reduced cell performance with increasing channel length is a trend that was observed.

The even cross flow rate in the short cell appears to be more advantageous when these results are compared to the experimental data and suggests that interdigitated designs are sensitive to maldistribution along the channel length. Neutron radiography is being conducted to study the water removal characteristics of interdigitated cells of varying length. Through-plane images of in-situ cell operation should allow for comparison of inlet and outlet water content as well as comparison of GDL water distribution. The effect of width and depth of channels are currently being examined. Channel dimensions of interest are (width x depth, in millimeters) 1x1, 0.5x0.5, 0.25x0.25, 0.5x1, 1x0.5 and 0.25x0.5.

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INTRODUCTION

Over the past few years, polymer electrolyte membrane fuel cells (PEMFCs) have been gaining traction in automotive and transportation applications. The Automotive Fuel Cell

Cooperation, founded in 2007 in Vancouver, is a collaboration between Daimler, Ford and Nissan to study the feasibility of various cell geometries. The AFCC does further research into the bounds of PEMFC technology, pushing it forward to an application to vehicular fuel cells. Hyundai is currently

developing a fuel cell powered version of the Tucson for initial release in Korea. Known as the Hyundai ix35 FCEV, it could be the first commercially produced fuel cell vehicle sold at mass market. Germany has announced a new program to invest \$500 million in hydrogen infrastructure along their highways, further increasing the viability of fuel cell powered vehicles.

In some situations, the end use of the fuel cell places significant constraints on its packaging shape and dimensions. Automobiles have a limited amount of space available to locate these power systems, so flexibility of design shape may be a useful feature for many manufacturers. In some PEMFC powered buses, the fuel cell unit has extremely long channels compared to their width. In parallel flow field configurations, increasing aspect ratio has been seen to increase the net power density of the PEMFC stack [1]. There are problems associated with parallel flow fields, such as increased water retention in the gas diffusion layer (GDL) [2].

Interdigitated flow fields induce convective transport (cross flow) through the porous GDL between adjacent channels and can remove water built up beneath land areas in the GDL, which can lead to higher cell performance for a given active area and reactant flow rate than parallel flow fields [3, 4]. However, the head loss due to flow down exceptionally long channels, among other factors, may cause cross flow maldistribution of reactants down the channel. Such maldistribution may lead to areas of low or areas of excess cross flow. This, in turn, can cause areas of low oxygen concentration and water build up, and therefore higher pressure losses and uneven membrane hydration, all of which reduce overall cell performance [5, 6, 7].

This research seeks to examine the affect varying channel aspect ratio has on cross flow and power density in an interdigitated flow field. This type of information will be useful for stack designers who may have constraints on the conformation of the stack. The research further seeks to understand the relationship between parasitic power and overall power, as it relates to aspect ratio. This type of information may be useful for minimizing losses in a stack.

SIMULATION FORMULATION

Geometry and Assumptions

The multiphysics package COMSOL was used to simulate the interdigitated flow field at varying lengths and conditions in three dimensions. Figure 1 is a breakdown of the computational domains modeled. The model focuses on the cathode flow field and GDL layer and does not take into account the electrochemical reaction. As this study is interested in how channel length affects pressure and cross flow distribution, modeling the entire electrochemical process is not necessary because the electrochemical reaction has little effect on bulk cross flow; additionally, the experimental portion

of this work characterizes cell performance. Reaction by-product water is a factor; however, no models can currently account for this completely. The model assumes the following:

- No electrochemical reaction
- Steady state operating conditions
- Isotropic and homogeneous GDL structure
- No effects from land area compression
- No mass transport across the GDL/CL interface
- Water exists only in a gas phase
- Water, nitrogen and oxygen are ideal gases
- Isothermal

Subdomains (Interdigitated)

- Inlet Flow Channels
- Outlet Flow Channels
- Gas Diffusion Layer (GDL)

All Channels: 1 mm x 1 mm
All Lands: 1 mm
GDL Thickness: 180 μ m

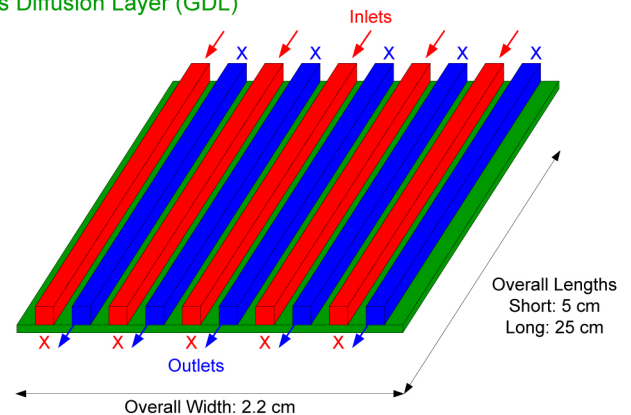


Figure 1. Subdomain geometries modeled in COMSOL. Arrows designate inlet/outlet flows while X's designate blocked boundaries on the channel domains

Governing Equations and Boundary Conditions

Conservation laws for compressible flow were applied to the flow field and GDL domains via:

Continuity equation:

$$\nabla \cdot (\rho \mathbf{u}) = 0 \quad (1)$$

Momentum conservation in the channels:

$$\rho(\mathbf{u} \cdot \nabla) \mathbf{u} = -\nabla P + \mu \nabla^2 \mathbf{u} - \frac{2}{3} \mu \nabla(\nabla \cdot \mathbf{u}) + \mathbf{b} \quad (2)$$

where ρ is the density of the gases, $\mathbf{u}$ is the velocity field, μ is the viscosity of the mixture, P the pressure and $\mathbf{b}$ accounts for body forces. A compressible formulation of the state equations was used in this simulation for added accuracy. To this end, the variation in density due to pressure was accounted for and included in calculations. Momentum conservation in the porous media (i.e. the GDL) was handled using the Brinkman modification to the momentum conservation equations [8].

$$\frac{\rho}{\epsilon} \left((\mathbf{u} \cdot \nabla) \frac{\mathbf{u}}{\epsilon} \right) = -\nabla P - \frac{2}{3} \frac{\mu}{\epsilon} \nabla(\nabla \cdot \mathbf{u}) + \frac{\tilde{\mu}}{\epsilon} \nabla^2 \mathbf{u} - \frac{\mu}{K} \mathbf{u} + \mathbf{b} \quad (3)$$

where K is the effective permeability, $\tilde{\mu}$ is the effective viscosity (following Brinkman's work, $\tilde{\mu}$ is set to μ) and ϵ the porosity [8].

In this simulation the inlet condition was determined by a laminar inlet velocity, calculated based on the mass flow of the gas at the maximum power point. The development length in the channel was small compared to the length of the cell. The edges of the channel were constrained to a velocity of zero, to model the wall condition. Due to the low Reynolds number throughout the cell, the outlet condition was also specified to be laminar. The outlet in the experimental cell vented to the atmosphere, so in the simulation, the outlet channels had a boundary condition requiring them to have an outlet absolute pressure of one atmosphere.

Mesh and Solver

The MUMPS direct solver in COMSOL was used to find solutions for [equations 1, 2, 3-5](#) based on the parameters specified and limited by the boundary conditions. The mesh in the 5 cm flow field had 102,900 rectangular mesh elements. The mesh in the 25 cm flow field contained 205,800 rectangular mesh elements. Increasing the number of mesh points and changing the mesh geometry resulted in pressure drop differences of less than 1%, indicating the solution was mesh independent at this level of fineness.

Parameter Selection

The channel and GDL properties listed in [Table 1](#) are based as closely as possible to the actual material properties of components used in the experimental portion; this was to ensure comparable results. Channel lengths, L_c , were selected based on a previous experimental study examining channel length effects on parallel design flow fields, which calculated the required pressure drop for water removal [1]. The resulting channel length to width ratios (channel aspect ratios) were 50:1 and 250:1. The simulation inlet velocities, u_{in} , were determined by examining the flow rates of the actual cells at maximum power and specified stoichiometry, then calculating the bulk velocity based on the entrance geometry. Simulations were run at both standard (1.5 Anode, 2.0 Cathode) and excess (2.0 Anode, 4.0 Cathode) stoichiometry based velocities.

Table 1. Properties for computational model.

Variable	Value				Description
	Short	Long	Short	Long	
	Normal Flow	Excess Flow	Normal Flow	Excess Flow	
T ($^{\circ}\text{C}$)	70	70	70	70	Temperature
P_{out} (Pa)	0	0	0	0	Outlet Press. (gage)
ϵ	0.50	0.50	0.50	0.50	Porosity of GDL
κ (m^2)	4.15e-13	4.15e-13	4.15e-13	4.15e-13	Permeability of GDL
t_{GDL} (mm)	0.18	0.18	0.18	0.18	Thickness of GDL
u_{in} (m s^{-1})	1	2	5	10	Inlet Velocity
w_c (mm)	1	1	1	1	Channel Width
d_c (mm)	1	1	1	1	Channel Depth
w_l (mm)	1	1	1	1	Land Width
L_c (cm)	5	5	25	25	Channel Length

SIMULATION DISCUSSION

Pressure Distribution

The overall pressure distributions of the flow-field channels, simulated at the excess stoichiometric based flow rates, are displayed in [Figure 2](#), while [Figures 3a & b](#) show the pressure within the center two inlet and outlet channels along the length of both cells. The parabolic trends visible in the long cell are due to head loss within the channel. Longer channels support a greater head drop down their length, and are thus prone to pressure differentials within the channel itself. By contrast, the short cell inlet channel pressure remains fairly constant down the length of the cell, while the outlet channel remains close to atmosphere. These results match previous interdigitated studies and are very similar to pressure distribution trends were observed by Koh et al. in their study of z-configuration PEMFC manifolds which have similarities to interdigitated flow field designs [9, 10].

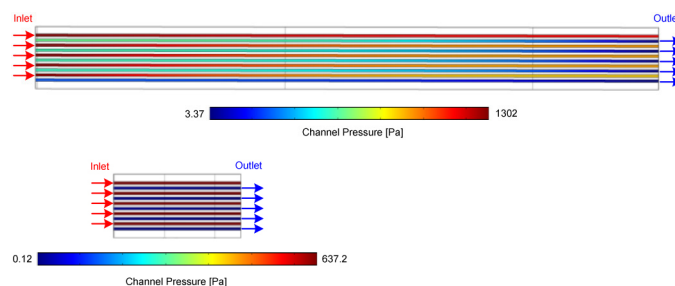


Figure 2. Overview of the channel pressure distribution in the higher flow rate case