Particle Image Velocimetry Measurements in a Model Proton Exchange Membrane Fuel Cell

Particle image velocimetry was used to measure 2D velocity fields in representative regions of interest within flow channels of interdigitated and single-serpentine proton exchange membrane (PEM) fuel cell models. The model dimensions, gas diffusion layer (GDL) permeability, working fluid, and flow rates were selected to be geometrically and dynamically similar to the cathode-side airflow in a typical PEM fuel cell. The model was easily reconfigurable between parallel, single-serpentine, and interdigitated flow fields, and was constructed from transparent materials to enable optical imaging. Velocity maps were obtained of both the primary and secondary flow within the channels. Measurements of the secondary flows in interdigitated and single-serpentine flow fields indicate that significant portions of the flow travel between adjacent channels through the porous medium. Such convective bypass can enhance fuel cell performance by supplying fresh reactant to the lands regions and also by driving out product water from under the lands to the flow channels. [DOI: 10.1115/1.2744053]

Keywords: PEM, PIV measurements, serpentine, interdigitated, convective bypass

Introduction
Convective flow affects several key processes of hydrogen PEM fuel cell operation. Particularly important in the cathode where diffusion is less dominant, these processes include the delivery of high-concentration reactant oxygen to the catalyst layer, removal of product water (vapor and liquid), and in some applications the removal of heat. There are two primary fuel cell components that determine the effectiveness of convection. The first are the bipolar plates, which affect the flow by means of the channel geometry. By tailoring the channel design, it is possible control the pressure gradients and velocity fields in fuel cells. The second component that affects convection is the gas diffusion layer. Despite its name, the gas diffusion layer is porous and thus capable of fluid convection when pressure gradients exist. The permeability of the gas diffusion layer then plays an important role in determining convective flow patterns.

Not surprisingly, there is a need to experimentally verify the effectiveness of convective flow in various fuel cell designs. Thus, the development of spatially resolved flow measurement techniques for fuel cell applications is a highly active area of research. Several researchers have developed transparent fuel cells primarily designed to qualitatively observe the transport of liquid water in hydrogen fuel cells [1,2] and carbon dioxide bubbles in direct methanol fuel cells [3–6]. One quantitative technique that has recently been developed is thermal neutron imaging [7–9]. This technique operates by directing a collimated neutron beam into a hydrogen fuel cell; the neutron beam is scattered by liquid water by an amount related to the thickness of water. By scanning the entire fuel cell, a 2D map can be created of water content in the cell. Despite the success and importance of these techniques, it must be noted that they observe the movement of product liquid water as opposed to the gaseous reactant species. Although computer models for predicting reactant flow have become quite sophisticated, the current problem would require a 3D computational fluid dynamics (CFD) code (either direct numerical simulation or coupled with the correct turbulence model) and a channel/GDL interaction model that must simultaneously solve for flow through the porous GDL.

Particle image velocimetry (PIV) can not only provide detailed velocity data for comparison and validation of such CFD models, but can also directly provide guidelines for improved flow field designs as well as choice of GDL materials.

Particle image velocimetry (PIV) is a technique used to obtain instantaneous 2D velocity fields. This is in contrast to techniques such as laser Doppler anemometry and hot wire anemometry, which have high temporal resolution but are pointwise and thus have low spatial resolution. The operating principle of PIV is as follows (Fig. 1). A fluid is seeded with passive tracer particles that are small enough to closely follow the streamlines of the flow. Then an illuminating source (typically, a laser sheet) emits two pulses of light that cast two images of the particles onto a recording medium (typically, a CCD camera). Because of the time delay between pulses, particles in the second image are displaced slightly from the first. A process known as interrogation is used to quantify the displacement field between the two images. To accomplish this, the two images are divided into many subregions known as interrogation spots which each contain small clusters of particles. Software is used to compute a discrete spatial cross-correlation between particles within the interrogation region; the point of maximum crosscorrelation determines the approximate x and y displacements of the particles [10]. Using subpixel interpolation, the displacement can be measured to within 0.1–0.2 pixels [11]. Knowledge of the time delay between illuminating pulses allows a velocity vector to be obtained in each interrogation region, allowing one to construct the entire 2D velocity field.

The most recent attempt to apply PIV to fuel cell operation was an investigation of centrifugally driven secondary flow at a U-turn similar to flow that would be found within the flow field in a fuel cell [12]. A dimensionally scaled model was constructed from acrylic in which two channels were connected by a square turn. PIV was able to determine that secondary flows associated with the U-turn are laminar for Reynolds numbers less than \( \sim 400 \); beyond this, turbulence ensures both in the corner and downstream. It was concluded that the reactant would be well mixed in the flow channel under such conditions. Although this apparatus

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was able to model the turbulent nature of the turns of a fuel cell, it did not model other aspects of convection in the fuel cell. Specifically, it could not observe channel convective bypass (flow that crosses from one channel to another via the porous media) because it did not contain a porous layer to simulate the gas diffusion layer.

In this paper, we seek to advance the use of PIV as a tool for evaluating flow channel designs by using it in conjunction with realistic channel designs that include a porous underside. In doing so, it will be possible to directly observe previously elusive phenomena, such as convective bypass into the gas diffusion layer.

Experimental Setup

The current study employs dimensional analysis in order to alleviate some of the technical difficulties that would be encountered while observing operational fuel cells. In the current approach, a primary assumption is that the convective flow of air in a fuel cell can be modeled by flow of a nonreacting, incompressible fluid, such as water, as long as the geometric and dynamic similarities are maintained. The fact that air is 79% nitrogen gives some justification for this, but it is ultimately an approximation. Then, since no attempt is made to duplicate the reaction physics, the special materials needed for fuel cell operation become unnecessary. Thus, the bipolar plate of the model can be made from transparent materials that allow the use of the optical imaging techniques used in this study. Likewise, the proton exchange membrane can be modeled as an impermeable boundary. In order to simplify the optical requirements of the experiments, it was useful to geometrically scale up the model by a factor of 10. Then, an important consideration becomes the nature of the model porous medium, whose permeability should also be scaled appropriately.

An experimental apparatus was constructed to measure velocity fields representative of those in a fuel cell. The flow field was designed to be dynamically similar to a 15 cm² fuel cell operating at an equivalent current density of 4 A/cm² (equivalent current density is defined as the product of the measured current density and the stoichiometry). The flow field is reconfigurable, capable of operating as a parallel, serpentine, or interdigitated network (see Fig. 2). The flow channels were constructed by bonding optically clear acrylic pieces together to form five parallel channels. The four internal ribs have dimensions of 360 mm × 9.5 mm × 9.5 mm. The flow channels are 9.0 mm wide and 9.5 mm tall. A buffer of 10 mm was left between the end of each rib and the outer viewing window. The basic channel configuration represents a parallel flow field. To create serpentine and interdigitated flow fields from the parallel configuration, rubber plugs were cut and friction fitted into appropriate regions of the acrylic base as indicated in Fig. 2. An aluminum spacer wrapped in polytetrafluoroethylene (PTFE) tape was used to provide the proper thickness of the porous medium as well as to seal the model from the surroundings. A solid aluminum plate was placed under the porous medium to act as the “impermeable” membrane. Finally, a top aluminum plate with cutouts for optical access was fastened to the bottom plate (see Fig. 3). Ports were drilled into the acrylic to serve as the inlet and outlet for fluid flow as shown in Fig. 2. A pump was used to circulate water from a reservoir into the apparatus. The water flow rate was controlled using an acrylic flowmeter with metering valve.

The region of interest was illuminated by twin Nd-YAG lasers (Continuum Surelite II), operating at 10 Hz, and providing 30 mJ per pulse (pulse duration=6 ns) at a wavelength of 532 nm. Spherical and cylindrical lenses were used to form a light sheet of appropriate thickness. Images were recorded on a CCD camera (LaVision ImagerIntense, 1280 × 1020 pixels) specialized for single-frame–double-pulse PIV. Fluorescent particles (20–40 μm) were used to seed the flow. By using fluorescent particles in conjunction with a long wave filter, background noise can be significantly reduced while retaining high particle image intensity. In a further attempt to reduce background noise and increase particle correlation, a background image (200 images averaged together) was subtracted from each PIV image. Image interrogation was performed using in-house software. An interrogation spot size of 64 × 64 pixels with a 50% overlap was used during post-processing. PIV was performed on the interdigitated and serpentine flow field geometries.
In order to describe the positions of the measurements, a coordinate system was defined (see Fig. 2). The channels were designated by numbers, number 1 being the closest to the inlet and number 5 being closest to the outlet. The dimension $z$ is used to describe the distance along the channel, while dimensions $x$ and $y$ are used to describe the width and height of each channel. Experiments in the interdigitated configuration focus on the observation of channel convective bypass. Cross-sectional images in the $xy$ plane were taken for several values of $z$ along channels 2 and 4, the exiting “fingers.” Images of the $yz$ plane were also taken in the center of all five channels in order to observe the primary flow near the finger edges of channels 1–3. PIV was conducted in the single serpentine configuration along $xy$. Cross-sections of channel 3 for several values of $z$. Channel 3 was chosen because its flow is anticipated to contain the flow pattern most similar to the spatially periodic flow encountered in the center of the prototype device. For cross-sectional images in the $xy$ plane, the laser sheet was directed vertically down into the channel through cutouts in the top aluminum plate and the camera viewed the illuminated region through the model end wall. For axial images in the $yz$ plane, the laser sheet was again directed down through the cutouts in the top plate, but the camera viewed the illuminated region through the sidewall of the model.

For both sets of experiments, multiple images (typically 75) were acquired and the instantaneous velocity fields obtained by interrogation were averaged in order to produce smooth velocity field plots. Images acquired deep within the channels were particularly noisy because of the large number of particles and glass fibers that block the optical path; for these regions, 200 velocity fields were acquired and averaged. The optical arrangement was determined as a compromise between several competing factors. For maximum accuracy in PIV, it is usually beneficial to allow particle displacements of several pixels; however, due to the out-of-plane motion of the particles, large particle displacements in the image plane can cause particles to exit the light sheet prematurely. This decreases the quality of the correlations performed during the interrogation stage. In order to correct for this, it was necessary to properly coordinate the pulse separation, laser sheet thickness, and lens f-number. In order to avoid imaging out-of-focus particles, the laser sheet thickness must be less than the depth of field of the optical device. The depth of field of a single lens and iris optical system is determined by the f-number according to

$$d_f = 4(1 + M^2)f\lambda$$

where $M$ is the magnification, $f$ is the lens f-number, and $\lambda$ is the wavelength of the scattered light. Thus, the depth of field is significantly improved by increasing the f-number. However, increasing depth of field through changes in the f-number has the undesirable effect of reducing the amount of captured light and perhaps more importantly reducing the quality of the image through an increased diffraction-limited spot size as given by

$$d_f = 2.44(1 + M)\lambda$$

Even at the modestly large f-number of 16, this yields the diffraction limited spot size of 34 $\mu$m, which is quite large compared to the geometric particle size of 20–40 $\mu$m. Thus, in order to accurately resolve particle displacements of several pixels, an f-number between 16 and 25 can be used to achieve high depth of field while avoiding undesirable diffraction effects. Pulse separation and light-sheet thickness can then be set to enforce particles to remain in the light sheet. The current study employs the criteria that at least 75% of particles should remain in the light sheet, which gives the final condition for the optical requirements that

$$\Delta t_{\text{max}} \leq 0.25 \frac{\delta c}{V}$$

where $\Delta t_{\text{max}}$ is the maximum pulse separation and $V$ is the primary velocity in the channel, which can be estimated a priori.

Then, for various regions of the PIV measurements, the pulse separation differs depending on the primary velocity in the channel and the desired particle pixel displacement. For the current experiments, this was between 0.1 ms and 10 ms with light-sheet thicknesses between 0.5 ms and 4 mm.

Care was taken to properly scale permeability of the porous medium that lies beneath the model “bioplate.” Permeability carries the dimensions of $L^2$. Thus, since the geometric scaling factor for the model is 10, the permeability must be scaled up by a factor of 100. Experimental data show that in-plane permeability for commercially available GDL materials can take on a wide range of values (5 $\times$ 10^{-13} m^2 to 5 $\times$ 10^{-11} m^2) [13,14]. An isotropic fabric consisting of randomly oriented e-glass fibers was found to be suitable, having an in-plane permeability of 1 $\times$ 10^{-10} m^2 at a thickness of 3.2 mm (determined by the technique described in [15]). This would then represent a GDL at the upper end of the permeability range with a thickness of ~320 $\mu$m. It should be noted that it is difficult to match all the anisotropic properties of the GDL. However, we have made the assumption here that the only property of the GDL that greatly influences flow is the in-plane permeability (which is matched between the model and the “prototype” fuel cells). Our assumption is justified by the relatively longer in-plane path the flow must travel under the lands, compared to the short through-plane travel under the channels. The fiber structures that produce that permeability may be different, but the permeability has been correctly scaled.

Note that although the intention of the experiments was to simulate a square cell with a 15 cm² active area under various configurations, the model has only five “passes” instead of the 19 or so that would exist in the actual cell. However, it is geometrically similar in all other aspects. The reduced number of passes has the advantages of allowing easier optical to access to the center channel and reducing the assembly burden, but has several repercussions related to achieving dynamic similarity. The most obvious shortcoming of having so few channels is that it causes a “finite width” affect. For a cell with 19 passes, it can be expected that the velocity field will eventually achieve a periodically repeating profile; the finite width of the model, however, may not be sufficiently long to allow the fluid to settle to it periodically repeating state. However, it is expected that by the third pass, flow in our model will closely resemble the periodic flow of the full 15 cm² cell. For dynamic similarity, the Reynolds number based on hydraulic diameter inside an individual channel should match between the model and the prototype. Because of the inexact geometric modeling, experimental parameters were modified appropriately to achieve dynamic similarity as closely as possible. For dynamic similarity, the interdigitated configuration requires less flow than an exact geometric model because the flow is being distributed through fewer channels; specifically, because the current model is 9 cm wide, whereas the exact geometric scaling would be 38 cm wide, the current model requires 0.23 (9/38) times the water flow rate of the exact scaling. Based on this rationalization, a water flow rate of 3.5 cm³/s was used while conducting experiments in the interdigitated cell configuration. The serpentine configuration does not require such a flow rate correction since flow is carried along a single channel regardless of the inexact geometric similarity. Thus, for experiments conducted in the serpentine configuration, a water flow rate of 15 cm³/s was used. Note that interdigitated and serpentine fuel cells operate at considerably different Reynolds numbers (350 and 1400, respectively, here) even though they have equivalent cell mass flow rates because of the way flow is distributed throughout the cell. Furthermore, the ratio of the interdigitated Reynolds number to the serpentine Reynolds number increases with cell area.

### Results

**Interdigitated Flow Field.** Because of the symmetry of the interdigitated flow field, it was anticipated that velocity fields in
Fig. 4 Velocity fields for interdigitated cell configuration. (a)–(f) correspond to the cross section and (g)–(k) represent the axial measurement. In (g)–(k), the $z_l=34$ cm and $z_f=35$ cm describe the location of the measurement (see Fig. 2 for coordinate system). Gray zones are regions with invalid data due to optical obstructions.
Fig. 4 (Continued).
Fig. 5  Velocity fields in channel 3 of the serpentine cell configuration. Gray zones are regions with invalid data due to optical obstructions.
Three return channels (1, 3, 5) shows that the velocity fields are all very similar. It is interesting that the velocity magnitudes near the edge of the fingers are still quite large compared to the cross-sectional components. This is not entirely unexpected since the Reynolds number at the inlet is 350, indicating the importance of fluid inertia. The stagnation of the flow at the right wall as it abuts the channel end (rubber stopper) is clearly evident. Also evident is that the flow then bends downward and exits via the porous medium towards the outlet manifold.

Velocity fields in the yz plane of the return channels are shown in Figs. 4(g) and 4(h). Since at this point of the cell, the two channels carry almost all of the return flow, the primary velocity is quite high near the center of the channel (≈30 mm/s). It has a near parabolic profile, such as that expected in a fully developed pipe flow. If we compare velocities in the primary direction with the secondary velocities, it is seen that the secondary velocity moves at only ~1% the speed of primary flow. Because this tends to promote out-of-plane loss of pairs in the PIV procedure, this makes measurement of the secondary velocities quite difficult as mentioned in the previous section.

Single Serpentine PIV. Velocity fields were determined in the cross-sectional xy plane of the center channel (channel 3) in a serpentine arrangement at various distances along the channel (denoted by the coordinate z). Figure 5(a) shows the flow just after the 180 deg turn. As expected, large secondary flows in the form of three vortices are present corresponding to centrifugally driven flow around the corner. The secondary vortices quickly diminish as seen in Fig. 5(b) just 5 cm from the turn. Flow appears to emerge from the porous medium at the left corner (x/w = 0) of the porous medium and exit at the right corner (x/w = 1); this is a clear view of the channel convective bypass, which is predicted by computational [16] and analytic [17] models. However, the emergence from the left side is somewhat surprising, given that very little pressure gradient exists between adjacent channels near the corner. One possible explanation could be that the inertia from the centrifugally driven vortices drives fluid into the porous layer. For similar reasons, the magnitude of the flow exiting at the right corner for large z was expected to be small. Again, this is not observed; flow exit at the right corner is nonzero and relatively even over all z locations as evident from Fig. 6. One aspect of the observations that is consistent with modeling is that in general, flow emerging from the bottom-left side of the velocity fields in Figs. 5(a)–5(b) appears to become more intense with increasing z.

Figure 6 shows the development of the flow along the z coor-
dinate. Although concurrent analytical modeling efforts [17] have made the simplifying assumption that anti-symmetry should exist in the velocity field along the $z$ coordinate, Fig. 6 shows that this is clearly not the case. One possible explanation is that since analytical efforts have neglected inertial effects, they may be incapable of predicting the true profile. However, there is another possibility. As stated earlier, the porous medium is composed of randomly oriented in-plane glass fibers that, when viewed macroscopically, has relatively consistent permeability; however, a visual inspection of the fabric shows that the pores are only slightly smaller than the scale of the channel. On this length scale, the permeability of the porous layer may not be a well-defined quantity. Thus, local variations in permeability may be to blame for the unevenness in the measured flow. This explanation would apply to both the serpentine and the interdigitated experimental results. In the future, it may be useful to use woven instead of random fabrics to model the fuel cells porous layer; this would at least distinguish the role of the porous layer in determining the smoothness of the channel bypass. However, it is possible that real fuel cells behave similarly to the current model, since real fuel cells often use randomly oriented gas diffusion layers with pore sizes only slightly smaller than the channel width.

Conclusions

In the current study, dimensional similarity was used to design a geometrically and dynamically scaled fuel cell model. The flow conditions in the model were selected to match the cathode-side airflow in an equivalent, albeit nonreacting fuel cell. Despite this limitation, the model allows several advantages that make it overwhelmingly simpler to perform PIV measurements than in an operational fuel cell. The first is that all the walls of the model are transparent, which has made it possible to measure channel convective bypass for the first time. Another simplification of the current method is that it admits the use of the other fluids (in this case water) as the working fluid in the fuel cell model. The model is easily reconfigurable between parallel, interdigitated, and serpentine flow fields, although velocity data were obtained only for the latter two. Velocity vector maps were obtained of both the primary and secondary flow in the channels. The secondary flow in the interdigitated case is two orders of magnitude smaller than the primary flow; thus, successful measurement of the secondary flow is a significant achievement of this study. The PIV velocity vector maps provide confirmation for our concurrent analytical study [17], which predicts the magnitude of convective bypass flow through the GDL. By dimensional similarity, the PIV velocity maps quantify the flow that would be expected in to-scale fuel cells. Our data reveal the presence of significant bypass flow through the GDL, indicating that convective transport dominates over molecular diffusion for the chosen conditions. Our data also reveal that reactant is not distributed evenly in serpentine configurations for the chosen conditions, whereas a more even distribution is seen for the interdigitated configuration.

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References