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Short communication

Experimental characterization of in-plane permeability of gas diffusion layers

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Abstract

Recent studies indicate that PEM fuel cell performance may be strongly influenced by in-plane permeability of the gas diffusion layer (GDL). The current study employs a radial flow technique for obtaining in-plane permeability of GDLs, using either gas or liquid as the impregnating fluid. A model has been developed and experimentally verified to account for compressibility effects when permeability measurements are conducted using a gas. Permeability experiments are performed on samples of woven, non-woven, and carbon fiber-based GDL at various levels of compression using air as the impregnating fluid. Woven and non-woven samples are measured to have significantly higher in-plane permeability compared to carbon fiber paper at similar solid volume fractions.

Keywords: Permeability; GDL; Fuel cells; Measurements; Porous media; Radial flow

1. Introduction

The gas diffusion layer provides five key functions for a PEM fuel cell: mechanical support for the proton exchange membrane, electronic conductivity, heat removal, reactant access to the catalyst layers, and product removal from it. The latter two functions are intimately linked to convective mass transport into and out of the gas diffusion layer and, for smaller fuel cells, heat removal as well. Therefore, it should be expected that the permeability of the gas diffusion layer is a key measure of the material performance. Experiments performed by Williams et al. [1] provide a correlation between through-plane permeability and limiting current density. However, in a recent review on gas diffusion layer characterization, Mathias et al. [2] points to in-plane permeability as the relevant parameter in fuel cell performance, citing diffusion as the dominant mechanism for through-plane transport. The view that in-plane permeability should be more relevant has been reinforced analytically by Feser et al. [3] as well as numerically by Pharaoh [4], particularly with respect to PEM fuel cells that employ serpentine flow fields. Other studies which have observed the effects of channel-to-channel convection have reported improved performance at high current density [5–8], again confirming the importance of enhanced convection. This is particularly well documented in interdigitated flow fields since forced convection is the primary motivation for them. However, computational models of interdigitated flow fields have shown that for a given stoichiometric ratio, changes to GDL permeability have negligible effect on cell performance [9]. This is logical since the total reactant penetration at a given stoichiometry into the GDL is the same regardless of GDL permeability; by design, it is 100%. However, even in this case higher GDL permeability clearly reduces the pumping power needed to maintain the given stoichiometry and thus is advantageous; the reduction in pumping power is, of course, unique to flow fields which utilize forced convection such as interdigitated flow fields and to a lesser extent serpentine flow fields. The pumping requirements of a parallel flow field would remain unaltered by a raised permeability. Also it is worth noting that computational models do not completely model liquid water formation, the removal of which may be expedited by increased GDL permeability.

While three of the five key roles of the gas diffusion layer are improved with increased convection, the need for low electrical contact resistivity apparently requires a design trade-off; electronic resistivity is reduced substantially by increasing compressive force whereas permeability (and therefore reactant and product mass transport) is reduced by it [10]. Polarization curves

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obtained at various levels of compression confirm that this is an important optimization process in fuel cell operation [11]. Thus, it is also desirable to know how permeability changes with compression.

The preceding discussion identifies a need in the fuel cell community for methods to measure gas diffusion layer permeability at various compressive loadings. Transverse or through the thickness permeability is most commonly measured, and several techniques for its measurement have been described [2,12,13]. Fewer techniques have been used to characterize the in-plane permeability of the gas diffusion layer. This will be the focus of the present work. Mathias et al. [2] describes a method in which two flow channels can be used to determine the in-plane permeability by measuring the relationship between pressure gradient and flowrate. While this technique is valid, achieving the necessary sealing can be difficult in practice because of the rectangular geometry. An alternative method is to measure the flowrate–pressure relationship in a radial-flow apparatus through an annulus of GDL material; sealing difficulties are alleviated by constraining the upper and lower surfaces of the annulus between two sufficiently flat and smooth plates. This measurement technique has been utilized in characterizing textile preforms in composites manufacturing [14–16]. However, the impregnating fluid is usually a viscous incompressible liquid. This method was recently adopted by Bluemle et al. [13] who compressed gas diffusion layers to measured force loadings in an Instron machine and determined their in-plane permeability by passing compressed air through an annulus while measuring flowrate and pressure drop across the layers. Assuming incompressibility of the gas and using Darcy's law, permeability was obtained from a least-squares fit of the data. An interesting aspect of this work is that the Darcy–Forchheimer convection model was used so that the experiment yielded both the viscous (Darcy) permeability and the inertial permeability. However, this was done only for through-plane permeability measurements as the inertial permeability was undetectable within the error bounds of measurement for the in-plane portion of that study. The current work had a similar experience with in-plane measurements.

The current work presents improvements to the existing techniques which allow in-plane permeability to be measured more accurately and with increased flexibility. Several difficulties arise in measuring in-plane permeability. First, the thickness of the gas diffusion layer can be quite small (some are as thin as 100 μm). This is on the same order of magnitude of typical machining tolerances; thus, any testing apparatus made by conventional techniques will introduce an element of uncertainty into the measurements due to uneven compression on the GDL leading to potential 'short-circuiting' pathways for the penetrating fluid. In the current study, an attempt is made to circumvent this effect by stacking multiple layers of material during experiments. For example, stacking eight layers of a 100 μm material raises the total thickness to 800 μm, for which a realistic machining tolerance of 25 μm allows the GDL to follow the contours of the machined surface to within about 3% of the total GDL thickness. To ensure that the 'nesting' between adjacent layers of GDL does not alter the outcome of the experiment, layers of thin, tightly toleranced shim stock can be used to separate each layer of the GDL stack.

A second difficulty addressed here is that because gas is used as the penetrating fluid, a truly compressible model of radially permeating flow should be used to fit the measured data. This is essential if the pressure difference used to drive the penetrating fluid is on the same order of magnitude as the absolute pressure of the fluid. An appropriate model, which is easily reducible to the incompressible case, is developed here for this purpose.

A third consideration that arises when measuring the permeability is that in order to have a well defined Darcy permeability, there should be a sufficient number of pores contained within the flow. For a typical gas diffusion layer, the majority of the void fraction is formed by pores between 10 and 100 μm in diameter [2]; thus, the distance traveled by the flow within the sample of material being tested should be on the length scale of centimeters for a reliable reading. It is interesting to note that most PEM fuel cells violate this principle since channel lands are typically about 1 mm wide, meaning that Darcy permeability is not strictly applicable on such length scales. To ensure that there are sufficient pores for consistent in-plane permeability measurements, the current study will employ much larger sample sizes than used in the Bluemle study [13]. Finally, an assumption is made that the in-plane permeability of the porous materials is transversely isotropic. The fabrics may exhibit slight degree of anisotropy in-plane but for practical purposes this can be ignored [17].

Using these improvements and assumptions, an apparatus was constructed and used to measure the in-plane permeability of several commonly available gas diffusion layers.

2. Measurement technique

2.1. Radial flow apparatus

A radial flow apparatus (Fig. 1) was fabricated to test samples of GDL for in-plane permeability at various levels of compressive strain. The samples consisted of annuli of material 15 cm o.d. × 9 cm i.d. stacked to a height of approximately 1 mm with each layer of material separated by a thin layer of brass shim stock (51 ± 5 μm each); as stated earlier, this was done to avoid nesting effects between stacked layers. Thicker shim stock was also used to control the total thickness of the compressed stack. For gas permeability experiments, compressed air (0–550 kPa) was introduced at the outer edge of the annular sample stack, forced through the sample in the in-plane direction, passed from the outlet at the center of the stack to a rotameter for flowrate measurement, and subsequently released into the atmosphere. In liquid permeability experiments, a pressurized tank (0–200 kPa) forced water though the sample and was collected in a graduated cylinder at the outlet. In the case of gas permeability, pressure was measured using gauges at both the inlet and the outlet as rotameters were found to introduce a significant pressure drop. For the case of liquid permeability, pressure was measured by a gauge on the inlet only and assumed to be atmospheric pressure at the outlet. The permeability measurement was accomplished by recording the pressure at approximately 10 different values of flowrate.