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Direct measurement of through-plane thermal conductivity of partially saturated fuel cell diffusion media

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HIGHLIGHTS

- Stress–strain relationship was measured to determine thickness and porosity of DM.
- Thermal conductivity was found highly dependent on compression and water content.
- Theoretical prediction of the maximum thermal conductivity was developed.
- Internal cell temperature difference was estimated as a function of saturation.
- PCI flow is more influential on multiphase transport with DM at lower saturation.

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ABSTRACT

An experimental study to investigate the through-plane thermal conductivity of three different diffusion media (DM) used in polymer electrolyte fuel cells (PEFCs) as a function of compression (from 0.1 MPa to 2 MPa) and saturation (from 0 to 25%) was performed. Additionally, measurements to determine the stress–strain relationship for the materials were made using an optical microscope. Both compression and water content had a significant impact on the through-plane thermal conductivity, which should be accounted for in multiphase modeling efforts. An analytical expression for the theoretical maximum of the through-plane thermal conductivity, as a function of both compression and saturation, was developed to help understand the nature of liquid connectivity in saturated pores. Additionally, a relationship was developed to predict actual thermal conductivity of the tested materials as a function of both compression and saturation based on experimentally measured data.

1. Introduction

Carbon paper is used as the diffusion medium (DM) in polymer electrolyte fuel cells (PEFCs) due to its suitable permeability, electronic conductivity, thermal conductivity, and mechanical strength. Thermal conductivity is a particularly important parameter, due to the interplay between heat and water management [1–4] and the perceived dominance of conduction heat transfer in PEFCs. Water generated in PEFCs that condenses into liquid phase must be removed to prevent loss of performance during operation and potential freeze–thaw degradation [5–8]. Polytetrafluoroethylene (PTFE) is normally used to improve hydrophobicity of the DM and reduce liquid accumulation. A highly hydrophobic microporous layer (MPL) is often utilized between the DM and catalyst layer (CL). The MPL is of great importance to mitigate flooding, to decrease electrical contact resistance, protect the membrane from damage from DM fibers, and prevent dryout from excessive vapor removal.

Various experimental approaches have been employed to measure the thermal conductivity of unsaturated DM [9–14]. Khandelwal and Mench [11] measured carbon paper and Nafion® membranes for PEFCs. They reported that Sigracet® 20 wt.% PTFE treated carbon paper had a thermal conductivity of 0.22 ± 0.04 W m^{-1} K^{-1} and Toray paper had a thermal conductivity of 1.80 ± 0.27 W m^{-1} K^{-1}. Burheim et al. [12] reported an increase of thermal conductivity of artificially aged SGL gas diffusion media while PTFE content decreases. They also measured SolviCore DM at different compression pressures. They reported that thermal

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conductivity increases as compression pressures grow and an increase in thermal conductivity when the DM is saturated [13]. Zamel et al. [9] measured the through-plane thermal conductivity of unsaturated Toray paper in a temperature range from −50 °C to 120 °C. A thermal conductivity of 0.8–1.8 W m^{-1} K^{-1} was reported at high compression, and 0.2–0.4 W m^{-1} K^{-1} at low compression. Although measurement of dry media is useful, in operation, PEFCs commonly have DM saturation at levels up to 30% [15–17]. Therefore, knowledge of partially saturated conductivity is important.

Several researchers also proposed numerical models to calculate thermal conductivity of DM [18–20]. In order to better understand the mechanism of water transport and its effect on performance and durability, Bazylak provided an overview of recent developments in liquid water visualization with PEFCs [21]. Yablecki et al. [22] reported an increase of 20.8% in through-plane thermal conductivity for their gas diffusion layer (GDL) modeling domain with 24.4% saturation. However, measurement of the thermal conductivity of diffusion media as a function of both compression and a full range of saturation has not yet been fully developed, so that the impact on transport can be fully understood, which is the motivation for this study. In this work, measurements of stress–strain relationship and thermal conductivity as a function of saturation were performed. A theoretical analysis of the maximum thermal conductivity as a function of saturation has been developed to glean insight into the internal distribution and connectivity of liquid in the media. Water transport within the saturated DM was also investigated via calculations of phase-changed-induced (PCI) flow and its impact as a function of saturation [23]. The results of this work should be useful to understand and more precisely model thermal transport in operating PEFCs with realistic saturation distributions.

2. Experimental setup

Diffusion media were uniformly compressed between two 25 mm thick stainless steel cylinders with known thermal conductivity. This design enabled determination of the stress–strain relationship and the through-plane thermal conductivity. Schematic diagrams of the experimental apparatus are shown in Figs. 1 and 2. A load cell was used to measure compression pressure on the diffusion media. All tests were performed at room temperature, which varied from 21 °C to 27 °C throughout the course of testing.

3. Design and instrumentation

A Hot Disk TPS2500S Thermal Constants Analyser (Hot Disk AB, Gothenburg, Sweden & ThermTest Inc., Fredericton, Canada) was used to measure the thermal conductivity of all materials tested in this work. Based on the theory of the Hot Disk Transient Plane Source (TPS) technique, a TPS sensor in the shape of a double spiral was utilized to take measurements within ten seconds, effectively decreasing unwanted water vaporization during the tests. The TPS sensor acted both as a heat source for increasing the temperature of the samples and a resistance thermometer for recording the time dependent temperature increases [24]. The reproducibility of measured thermal conductivity using this technique was observed to be ±3%. A TPS 7280 thin film sensor with a sensor diameter of 29.34 mm was used for all testing. This large format sensor provides a uniform heat flux across the measurement area.

4. Measurement and uncertainty analysis

Round, 53 mm diameter samples were used for stress-strain measurement. Mitsubishi Rayon Corp. Grafil U-105 (MRC 105), SGL Sigracet® 25 BC, and General Motors (GM) Experimental virgin samples were used in this study. GM Experimental samples are materials that satisfy the 2015 US DOE performance targets while enabling progress toward the automotive fuel cell system cost target of $30/kWe as developed under DOE Award Number *DE-EE0000470*. To reduce measurement error, two samples of MRC 105, SGL 25 BC, or GM Experimental were layered for each stress–strain measurement. Images of compressed samples were captured using a zoom stereomicroscope (Unitron ZST) and digital CCD camera (Olympus DP 73) with optical resolution of 1600 × 1200 pixels. Deflections of the DM in the images were measured using digital imaging software cellSens Standard.

In this study, the DM stress–strain relationship was optically measured, as shown in Fig. 3. The thickness versus compression relationship was then used to calculate the thickness used in the determination of compressed DM thermal conductivity. Porosity is of great importance to calculate the actual saturation of the porous media. As compression increases, the void volume in DM is reduced, decreasing effective porosity according to the following equation:

$$\phi^* = 1 - \frac{1-\phi}{1-\varepsilon} \tag{1}$$

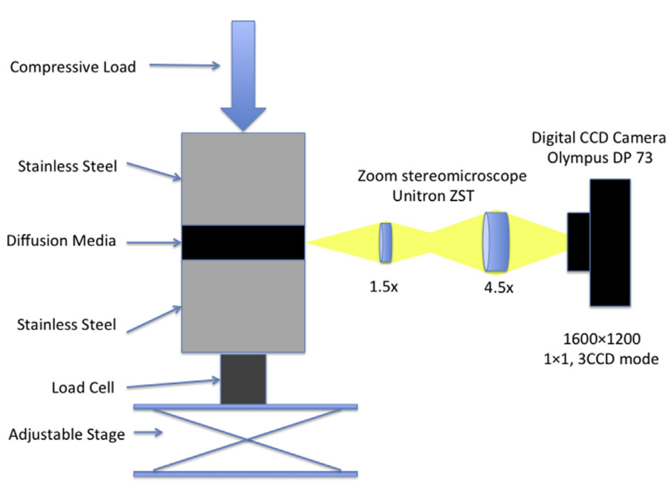

Fig. 1. Schematic diagram of the experimental apparatus used to optically measure stress–strain in thin film materials (not to scale).

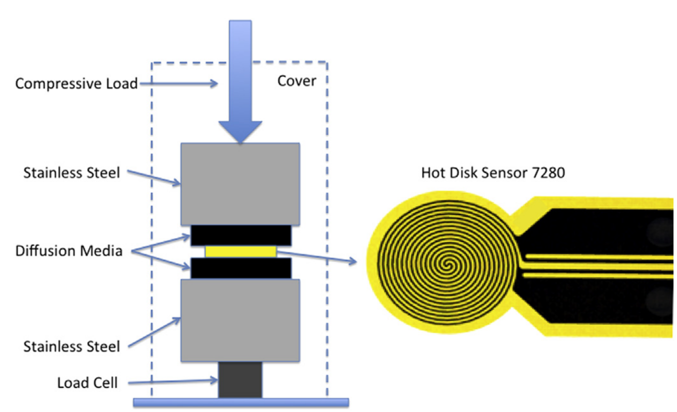

Fig. 2. Schematic diagram of the experimental apparatus used to measure thermal conductivity of thin film materials (not to scale).