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Heterogeneous porosity distributions of polymer electrolyte membrane fuel cell gas diffusion layer materials with rib-channel compression

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ABSTRACT

In this study, X-ray Computed Tomography (X-CT) is used to study the structure of the bi-layered gas diffusion layer (GDL) of polymer electrolyte membrane (PEM) fuel cells. This work presents a unique, calibrated segmentation procedure developed in-house to identify the distinct components of the bi-layer GDL, isolating the carbon fibre, the microporous layer and the void regions as individual phases. The novel use of the areal mass and areal volume of the GDL facilitates calibrated, reliable and repeatable multi-component segmentation and removes the high degree of subjectivity that might otherwise be encountered in typical thresholding procedures. Samples with and without MPLs are studied for the impact of rib – channel compression on porosity profiles. Under the channel, the porosity profile is nearly identical to the uncompressed profile. Under the land region, there is a significant decrease in the GDL thickness. It is also observed that the majority of the compression is exhibited by the substrate region while the MPL undergoes significantly reduced compression.

Introduction

The gas diffusion layers (GDLs) in polymer electrolyte membrane (PEM) fuel cells are responsible for providing distribution pathways for the reactants while also facilitating the removal of water in both gaseous and liquid phases. The reactants diffuse from the gas channels to the catalyst layer while the generated water must travel from the catalyst layer to the gas channels. The GDLs used in PEM fuel cells are typically bi-layered with a carbon fibre paper substrate and a microporous layer (MPL). The GDL is typically treated with a hydrophobic coating of polytetrafluoroethylene (PTFE), to enhance liquid water removal. Detailed reviews discussing the structure, properties and characteristics of GDLs are available in the literature [1–3].

A variety of techniques are often used to study the structure of GDLs. Mercury intrusion porosimetry is a commonly used technique to understand the pore size distribution [4,5], while atomic force microscopy or optical profilometry can be

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used to characterize surface features such as surface roughness [6]. Permeability and effective diffusivity can be directly measured using ex-situ measurement techniques [7,8], and other transport parameters such as thermal and electrical conductivity have also been directly measured [9,10].

X-ray Computed Tomography (X-CT) is an advanced imaging technique that has been used to study the internal structure of GDLs [11–18]. The major advantages of using X-CT to investigate the internal structure of these porous layers is its non-destructive nature, high resolution and the ability to obtain phase differentiated data for use in heat and mass transport models. GDL samples can be scanned with this tool to obtain highly-resolved three-dimensional (3D) micro-structures, which can be analysed with image processing algorithms to quantify its porosity [12], investigate structural and other parameters. This technique is useful for studying the heterogeneous pore structure of the GDL, from which pore size distributions can be determined for informing transport property models [19–22].

Fishman et al. [12] employed X-CT to compare the through-plane porosity distributions of paper, felt, and cloth GDLs. They observed that while felt and paper GDLs possessed surface and core regions in their through-plane porosity distributions, these regions could not be distinguished in the cloth GDL. Compared to the paper GDL, the felt GDL was observed to exhibit a more uniform core region. Fishman and Bazylak [14,23] also examined the effect of PTFE treatment and microporous layer (MPL) application on through-plane porosity distributions. The PTFE treatment was observed to be non-uniform, and it predominantly resulted in a decrease in the GDL surface porosity. The decrease in near-surface porosity due to the MPL was also observed from their X-CT investigations.

The aforementioned investigations provided valuable insights into the heterogeneous porosity distributions of uncompressed paper, felt, and cloth GDLs. Although these heterogeneous porosity distributions were subsequently utilized in numerical models that predicted liquid water distributions in GDLs [24] and the GDL thermal conductivity [20], the effects of GDL compression on the through-plane porosity distributions have not been fully investigated. The compression of the GDL is typically tuned to improve fuel cell performance [25–28]. Ge et al. [25] observed that for both paper and cloth micro-structures, there were optimal compression ratios for maximum fuel cell performance. They also noted that compression affected the performance with the use of a paper GDL to a greater extent than that with a cloth GDL. Roshandel et al. [29] found that a decrease in the average porosity led to decreased oxygen consumption, which was detrimental to fuel cell performance. Moreover, they noted that the change in porosity had a greater effect on the fuel cell performance at higher current densities.

Several authors have investigated porosity profiles of gas diffusion layers of PEM fuel cells using X-CT [11–18]. In 2010, Pfrang et al. [30] used CT techniques to image the structure of the GDL, and they examined the thermal contact region between the fibres to calculate thermal conductivity. In the same year, Fishman et al. [12] reported through-plane porosity distributions and showed the degree of variation in local porosities for carbon paper, felt and cloth GDLs.

In 2011, Fishman et al. [14] showed that the hydrophobic treatment of Toray carbon fibre paper led to non-uniform distributions of PTFE. Similar results have also been reported by Odaya et al. [31]. Fluckiger et al. [32] investigated the porosity profiles and saturation profiles of Toray samples, and they noted that water tends to accumulate preferentially in low porosity regions.

Often, CT techniques have been used to generate the computational domain for transport property modelling. Becker et al. [33] studied the impact of compression on bulk porosity, diffusivity and permeability. They used uniform compression and showed a significant reduction in transport properties with the increase in compression. Totzke et al. [18] observed that GDL compression resulted in a decrease in the bulk porosity and a shift of the pore size distribution to smaller pores for Freudenberg GDLs with MPLs. The tortuosity remained unaffected by the compression.

More recently, several authors have investigated the impact of rib-channel compression on GDL porosity in order to examine the compression experienced by the GDL in a commercial fuel cell system. James et al. [34] investigated the impact of rib-channel compression on an SGL 30BA GDL (substrate only) and reported that the effective transport properties varied by a factor of two between the rib and channel regions. In line with the findings of Fluckiger et al. [32], Zenyuk et al. [15] showed that in-plane porosity profiles of GDLs change significantly between the rib and channel regions, and they also found that liquid water accumulation was more pronounced under the channels (regions of lower porosity).

Pfrang et al. [35] segmented a bi-layered GDL (substrate with MPL). They experimented with several thresholding techniques in order to distinguish between the MPL and substrate, and their image processing included the use of diffusion filtering and greyscale thresholding. Hasanpour et al. [36] acknowledged the challenges associated with image thresholding, and they reported their use of the rolling ball method for thresholding on the substrate in their study. Khajeh-Hosseini-Dalasm et al. [37] used mercury intrusion porosimetry (MIP) to measure bulk porosity, and then they used these measured values to calibrate their image processing threshold levels. Sezgin and Sanker [38] provided a detailed comparison of various thresholding techniques. Other thresholding techniques that have been used to binarize a GDL image include the use of Otsu's method by Fishman et al. [12] and the use of a visually determined threshold and AMIRA's filament tracing method by Jhong et al. [39]. The impact of compression on the porosity profiles of bi-layered GDLs has not been analysed in the literature and would be valuable for predicting variations in transport properties under the rib and channel regions.

When dealing with the MPL, Fishman and Bazylak [23] developed a method to identify the MPL region separately from the fibrous portion of the uncompressed material. However, thresholding techniques could stand to be improved via calibration, such as with the inclusion of the mass of material contained in the sample. Current techniques typically rely solely on the distribution of image brightness to recognise void and solid regions, and with this relative brightness providing the only guidance to image thresholding, a variety of possible thresholding levels might be proposed for