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Impact of polymer electrolyte membrane fuel cell microporous layer nano-scale features on thermal conductance

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HIGHLIGHTS

- Nano-scale characterization of MPL materials.
- Atomic force microscopy used to analyse MPL particles and nano-features.
- Numerical determination of thermal resistance between MPL particle structures.
- Data presented for use in future stochastic MPL models.

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ABSTRACT

In this study, the microporous layer (MPL) of the polymer electrolyte membrane (PEM) fuel cell was analysed at the nano-scale. Atomic force microscopy (AFM) was utilized to image the top layer of MPL particles, and a curve fitting algorithm was used to determine the particle size and filling radius distributions for SGL-10BB and SGL-10BC. The particles in SGL-10BC (approximately 60 nm in diameter) have been found to be larger than those in SGL-10BB (approximately 40 nm in diameter), highlighting structural variability between the two materials. The impact of the MPL particle interactions on the effective thermal conductivity of the bulk MPL was analysed using a discretization of the Fourier equation with the Gauss-Seidel iterative method. It was found that the particle spacing and filling radius dominates the effective thermal conductivity, a result which provides valuable insight for future MPL design.

1. Introduction

Polymer electrolyte membrane (PEM) fuel cells are electrochemical energy conversion devices, and have been a main focus of study in the area of clean energy systems in the past decade. PEM fuel cells generate power electrochemically, utilizing hydrogen gas and oxygen from air, forming only water and heat as by-products. Aside from being an alternative energy system, PEM fuel cells offer other advantages, such as maintaining high efficiency during operation (50%–60% conversion efficiency) [1], supplying a high power to volume ratio (0.7 W/cm^3), operating with little to no noise, and being able to quickly reach steady state conditions [2] due to their relatively low operating temperature, ranging from approximately 60–80 °C [3–5]. In spite of these advantages, PEM fuel cells have issues regarding their cost [6], durability [7,8], and reliability [6].

These limitations can be minimized by optimally designing cell components, and by designing cathode materials for enhanced water and thermal management. For example, while heat is produced from the exothermic electrochemical formation of water near the cathode microporous layer (MPL) and catalyst layer (CL) interface, heat is also produced from joule heating (ohmic resistance to electron flow in the solid-space of the diffusion media) [4,9]. Heat is also introduced with the inlet gases, which facilitates higher humidity in the cathode of the PEM fuel cell for maintaining polymer electrolyte membrane hydration. Although water is required to hydrate the membrane, excess water in the MPL causes mass transport losses (attributed to the increased tortuosity of the path reactant gases must take to reach the reaction sites) [10–13].

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Also, during operation, delamination in the MPL-CL interface may occur due to the fluctuation of water levels caused by temperature changes [2]. Finally, heat sinks and sources are introduced whenever water evaporates or condenses, respectively, and are dependent on the local saturation pressure and temperature, which further complicate the cathodic temperature gradient and pathway for thermal conduction [14]. Nonetheless, there is a delicate balance between the water saturation and temperature levels in the PEM fuel cell which must be controlled in order to optimize performance, by avoiding excessive condensation of water from cooling, or material dry-out from overheating. Therefore, understanding how material structures affect heat transfer, water permeability, and gas diffusion is critical for advancing the design of cell components.

1.1. The microporous layer

The MPL is a nano-porous material, composed of agglomerations of carbon particles which range in diameter (on the order of nanometres), bound together with polytetrafluoroethylene (PTFE) filling [15]. Fig. 1 shows a scanning electron microscopy (SEM) image of commercially available SGL-10BB. The fabrication of the MPL generally involves spraying a mixture of carbon black particles (typically Vulcan XC72) with PTFE suspended in a fluid matrix onto one of the surfaces of the GDL (though other fabrication techniques exist) [16,17]. The MPL coating can be either fully-immersed, where the MPL exists within the pore-space of the GDL, partially-immersed, where part of the MPL is within the GDL pore-space and the other part is its own layer, or as a standalone structure [4]. The MPL coating has been reported to enhance the performance of the PEM fuel cell by allowing the cell to operate at higher current densities [18], due to the materials highly hydrophobic nature [19]. The MPL also improves the structural integrity of the cathode by protecting the membrane from overhanging GDL fibres, which may puncture the membrane and cause reactant crossover [20].

As can be seen in Fig. 2 (obtained via backscatter scanning electron microscopy), the structural features of the MPL are two orders of magnitude smaller than those of the fibrous gas diffusion layer (GDL). Characterization of the MPL material is difficult due to the small size of the structural features [15], and the lack of knowledge regarding the MPL structural variability [21], making modelling of the MPL (with respect to its nano-features) more challenging. For example, Nanjundappa et al. [21] analysed the effective thermal conductivity of the MPL as a standalone structure using focused ion beam-scanning electron microscopy (FIB-SEM)

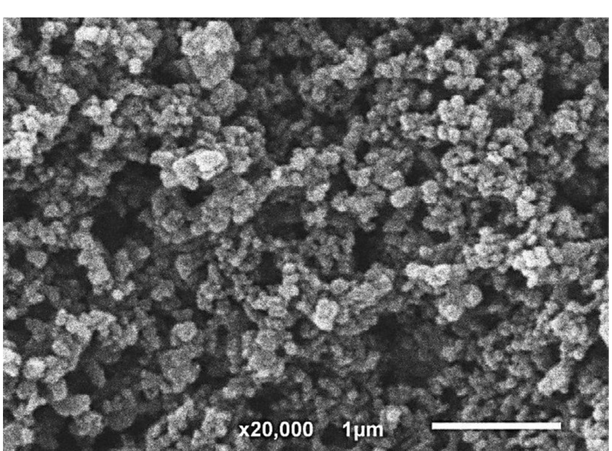

Fig. 1. SEM image of SGL-10BB showing variance in particle sizes.

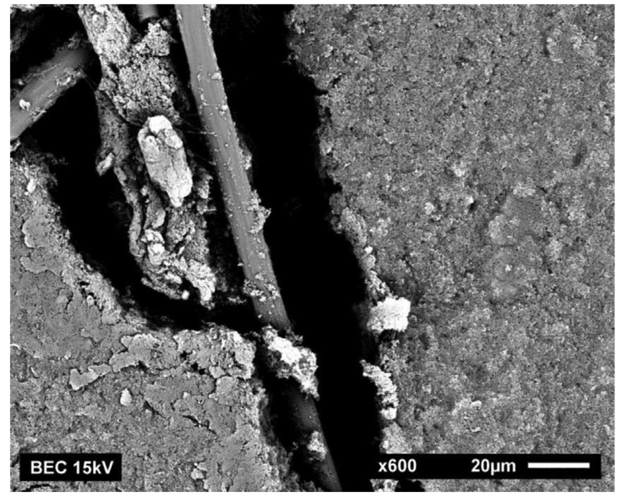

Fig. 2. Backscatter electron microscopy image comparing GDL fibre size, MPL crack width, and MPL pore size.

with a minimum voxel size of 8 nm × 8 nm × 10 nm. Nanjundappa reported that the MPL effective thermal conductivity is approximately isotropic, ranging from 0.13 to 0.29 W m^{-1} K^{-1} in its uncompressed state [21]. The MPL effective thermal conductivity range presented in Ref. [21] varied based on solid content used in the MPL reconstruction, which directly impacted the thermal resistance between MPL particles. This range in MPL effective thermal conductivity values reported in literature [20,21] highlights the need for a higher resolution 3-dimensional reconstruction of the MPL material, or an accurate stochastic representation of the MPL material. The level of resolution for accurate MPL effective thermal conductivity modelling must be high enough to isolate the contact area between the particles (a main parameter in determining the effective thermal conductivity).

Becker et al. [15,20] studied the MPL effective thermal conductivity dependence on the MPL structure, by reconstructing the MPL material stochastically using a constant particle diameter of 40 nm and filling radius between particles of 10 nm as input [20]. They found that the MPL effective thermal conductivity increases with decreasing mean pore size, with results being dependent on the porosity of the structure [20]. The MPL model reported in Refs. [15,20] is based on reconstruction with generic MPL nano-features, such as the particle size and particle spacing, but does not consider the impact of structural variability affected by the particle diameter and MPL particle filling radius. The variability of the MPL structure amongst manufacturers will act as a necessary input for modelling of specific MPL materials, and to the best of the authors' knowledge has yet to be studied in the literature.

In this study, commercially available SGL-10BB and SGL-10BC was analysed using atomic force microscopy (AFM), with a resolution of approximately 2 nm per pixel, to obtain the material-specific particle diameter and particle contact filling radius distributions. The information obtained can be used as inputs into future stochastic models of SGL-10BB and SGL-10BC, required for validation since MPL structures vary with manufacturer. We have also analysed the effect of varying the nature of contact between MPL particles on the effective thermal conductivity. This information is useful in guiding future stochastic models in their assumptions regarding the MPL particle-to-particle connections. By developing accurate models of the MPL materials, improvements to the PEM fuel cell design and performance in terms of performance and reliability can take place.