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The impact of fibre surface morphology on the effective thermal conductivity of a polymer electrolyte membrane fuel cell gas diffusion layer

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HIGHLIGHTS

- Nano-scale analysis of untreated GDL within a PEM fuel cell.
- Atomic force microscopy used to analyse surface roughness of carbon fibres.
- Analytical analysis of rough contact area and thermal contact resistance.
- Empirical formulations provide realistic inputs for thermal conductivity models.

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ABSTRACT

In this work, the effect of fibre surface morphology on the effective thermal conductivity of the gas diffusion layer of a polymer electrolyte membrane fuel cell is presented. Atomic force microscopy was used to measure the fibre surface roughness and asperity height distributions for various fibres for Toray carbon paper. Hertzian contact mechanics was used to determine individual micro-contact areas and thermal resistances, and results were compared with the smooth cylinder approximation. The effective thermal contact resistance between rough fibres was determined using resistance network theory. The thermal contact resistance and total contact area were determined for various angles of fibre orientation and contact forces; results are presented as empirical formulations. It was found that the effective thermal contact resistance is significantly affected by fibre roughness features when compared to the smooth fibre case, which is often used in the literature. The analysis conducted provides an alternative to computationally expensive surface feature analyses by providing a tool which can be used to implement the nano-scale features of gas diffusion layer fibres into existing effective thermal conductivity models.

1. Introduction

Polymer Electrolyte Membrane (PEM) fuel cells are electrochemical energy conversion devices that have the potential to generate electricity with zero local greenhouse gas emissions, when fed oxygen from air and hydrogen gas. An understanding of how thermal energy transfer and generation affect cell performance and tunability is needed before PEM fuel cells can be produced for commercial products. The porous gas diffusion layer (GDL) provides the main pathways for thermal conduction out of the cell through the solid phase, consisting mainly of stacked carbon fibres. During operation, the exothermic electrochemical reactions involved in water generation, and as well as ohmic resistances caused by electrical current, form temperature gradients within the cathode of the GDL. These thermal gradients affect the cell's relative humidity, water saturation, and reaction kinetics [1], which are coupled to the overall performance of the cell. It is therefore crucial to understand how the structure of the GDL can be optimized to effectively transfer heat out of the cell.

Several thermal conductivity models exist for analysing thermal conduction within the PEM fuel cell. Lattice Boltzmann methods have been used for determining the through-plane and in-plane thermal conductivity of the GDL [2–4]. Wang et al. [2] used lattice Boltzmann methods to analyse the effective thermal conductivity of unsaturated GDLs. They found that the in-plane effective thermal conductivity increases with fibre volume fraction and fibre

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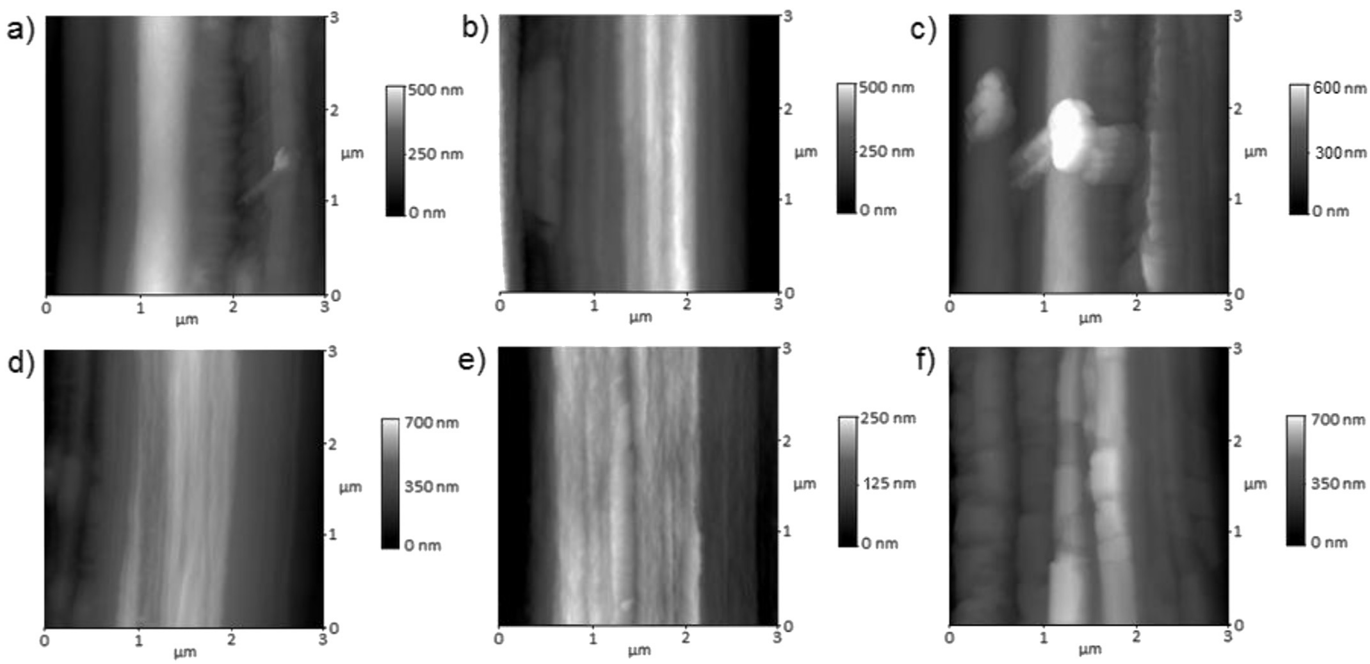

Fig. 1. AFM images used in rough contact analysis.

length, approaching a stable value when the fibre length becomes sufficiently long [2]. The authors also found that the through-plane effective thermal conductivity is inversely proportional to the porosity of the GDL, which was supported in lattice Boltzmann studies presented by Yablecki et al. [2,3]. Yablecki et al. [4] also determined the effect of GDL water saturation on the effective thermal conductivity. It was found that the effective thermal conductivity of the GDL increases with increasing water saturation, with a more significant effect in the through-plane direction rather than the in-plane direction [4]. Yablecki et al. [1] also used an analytical model to determine the effective thermal conductivity of compressed GDLs. Their approach was based on resistance network modelling, which was first explored by Sadeghi et al. [5,6]. It was found that the thermal resistance in the GDL is dominated by the fibre-to-fibre contacts, and the through-plane effective thermal conductivity increases linearly with GDL compression.

Although the effective thermal conductivity of the GDL has been studied, it was commonly assumed that the surfaces of the carbon fibres are smooth. In this study, the impact of incorporating realistic fibre surface morphology, in particular the circumferential fibre roughness, in effective thermal conductivity models is investigated. The results of this study could be incorporated into other existing effective thermal conductivity models, further improving their accuracy. Using an analytical approach based on Greenwood's rough contact model [7], the thermal contact resistances and contact areas between rough fibres housed in the GDL are analysed. The results obtained for various fibre orientation angles and contact forces are compared to the smooth fibre cases found in the literature and are presented with empirical formulations representing the mean and standard deviation of the contact areas and thermal contact resistances.

2. Experimental analysis

Carbon fibres housed in untreated Toray GDL were analysed using atomic force microscopy (AFM), located at the Canadian Centre for Electron Microscopy at McMaster University, Ontario. A Nanoscope IIIa Multimode (Digital Instruments) atomic force microscope was used to image Toray TGP-H-120 carbon fibre paper without polytetrafluoroethylene (PTFE) treatment. Fibres from the top layer of the GDL were imaged to obtain the following surface feature information: roughness in the circumferential and longitudinal directions, surface area, and height deviations caused by protruding asperities or irregularities. Here it is important to note that the longitudinal roughness differs from the fibre waviness. The roughness in this context can be viewed as the deviation in the distance from the fibre surface to the central axis of the fibre in the direction considered (circumferential or longitudinal). The waviness however can be viewed as the path which the central axis of the fibre follows, where a straight central axis would correspond to a non-wavy fibre [8].

Multiple fibres were analysed, from which six sections were imaged. These sections are representative of the various types of surfaces of carbon fibres exhibited in the AFM analysis. AFM images from two locations for three fibres within untreated GDL samples are shown in Fig. 1. The six AFM images in Fig. 1 feature large and small asperities (image *b* and image *f*, respectively), protruding irregularities (image *a* and image *c*), localized flat-zones (image *e*), and sharp peaks (image *d*). A scanning frequency of 1.001 Hz was used to obtain the images with dimensions of 3 μm by 3 μm. The image dimensions were determined by the expected size of the contact area shape based on findings from previous studies assuming smooth fibre contact [1,6]; the contact area does not exceed this boundary for the forces and orientation angles

Table 1
AFM image surface feature data.

AFM image	RMS roughness [nm]	Surface area [μm^2]
a	64.794	10.322
b	50.782	10.427
c	95.808	11.895
d	53.864	10.639
e	23.361	9.807
f	75.411	11.443