Applied Energy 231 (2018) 127–137

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Electrical resistance and microstructure of typical gas diffusion layers for proton exchange membrane fuel cell under compression

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HIGHLIGHTS

- Gas diffusion layer accounts for as much as 20% of the resistance in fuel cells.
- Parallel fiber microstructure leads to lower electrical resistance.
- Resistance of carbon paper and carbon cloth declines as the load cycles increases.
- Fiber crack and loss in resistance occur when exceeding "break stress" of 2.0 MPa.
- Carbon felt has the highest stability in electric resistance and microstructure.

ARTICLE INFO

Keywords:
Gas diffusion layers (GDLs)
Cyclic load
Steady load
Fiber microstructure
Electrical resistance
Fiber crack

ABSTRACT

Electrical resistance accounts for a significant part of the performance loss in proton exchange membrane fuel cells. To the best of the authors' knowledge, this work represents the first direct experimental investigation and comparison of the bulk resistance and microstructure of commercially available gas diffusion layers, carbon paper, carbon cloth and carbon felt, under cyclic and steady loads, which are typical compression conditions in the fuel cell. It was found that with the improvement of contact conductivity between gas diffusion layer and bipolar plate, the bulk resistance of gas diffusion layer accounts for as much as 20% of the resistance in the fuel cell, especially when the assembly pressure is high enough. Experimental results indicate that three kinds of gas diffusion layers show various electrical behaviors under compression due to their different fiber structures. For carbon paper, the resistance displays a gradual decline as the load cycles increases. A reduction in the resistance and obvious fiber cracks are observed when the compression pressure exceeds the "break stress" of 2.0 MPa. For woven carbon cloth, more uniform decline of the resistance is caused by the increasing fiber cracks, which are pulled and bent in the middle of a weave. Although felt gas diffusion layer features the lowest electrical conductivity, its tortuous and thick fibers lead to higher stability in electric resistance and microstructure than bonded carbon paper and woven carbon cloth. This study is helpful for enhancing our understanding of the relationship between electrical resistance and compression loads in the fuel cell with various gas diffusion layers.

1. Introduction

Proton exchange membrane (PEM) fuel cells have extensive potential applications in vehicles, portable devices and stationary power plants by virtue of the high efficiency, low pollution and quick start-up time [1]. A typical PEM fuel cell is composed of a bipolar plate (BPP) and membrane electrode assembly (MEA), which is in a five-layer structure with a center membrane, two coated catalyst layers (CLs) and two gas diffusion layers (GDLs). The compressed GDLs play multiple roles during the cell operation, such as: (1) transportation of reactant gases to CLs; and (2) removing produced water and heat from the MEA to BPP; (3) conducting electrons from the CLs to BPP [2]. As porous carbon-based materials, these functions are strongly affected by the fiber microstructure of the GDLs [3]. Understanding the porous GDL's characteristics in the compressed stack is critical to improving performance of the fuel cell.

GDLs are typically made of carbon fibers in porous structure. Extensive work has been conducted to develop GDLs with improved

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https://doi.org/10.1016/j.apenergy.2018.09.117
Received 6 January 2018; Received in revised form 6 September 2018; Accepted 10 September 2018

efficiency of the transport behavior and water management by means of experimental and numerical analysis. For the experimental attempts, optical photography [4–6], synchrotron X-ray [7,8] and neutron imaging [9,10] have been adopted to investigate the visualization of liquid water and microstructure in the GDL. According to the experimental results, it is recognized that the water removal is significantly affected by the GDL properties, such as pore dimension, wettability, especially when the fuel cell is operated at a high power density [11]. Compared with experiments which have limitation in the spatial and temporal resolution of mass transport, numerical simulation, such as pore network model [12,13] and lattice Boltzmann method [14,15], provides an effective tool for investigating the mass transport characteristics with microscopic view, and the fiber microstructure of the GDL is given sufficient consideration. The volume of fluid (VOF) method was also adopted to investigate the gas permeability of GDLs on the cell performance in Refs. [16,17]. In addition, in order to improve the power performance of the PEM fuel cell, GDLs are also designed by controlling the poly-tetrafluoroethylene (PTFE) [18,19] and micro-porous layer (MPL) [11,20] to possess the combined and balanced properties of hydrophobicity (water expelling) and hydrophilicity (water retaining). It can be seen that many advancements have been made to correlate the fiber microstructure to transport properties qualitatively and quantitatively in previous studies.

However, less attention is paid to the electrical conductivity of the porous GDL, which is an important part of the electrical resistance in the cell and affects the final output performance. According to Kleemann et al. [21], the through-plane conductivity of the GDL significantly influenced cell performance at low compression. This finding is in accord with the work of Radhakrishnan and Haridoss [22]. However, most of current studies assumed the GDL as a solid material with specific constant resistivity or without resistance in the fuel cell, such as Refs. [23–25]. Actually, the bulk resistance of the GDL is determined by its fiber microstructure [26], which means that the electrical conductivity of the GDL would be changed with the assembly force in the fuel cell. The thickness and electrical properties of the GDL also showed a dependence on load cycles in Radhakrishnan et al.'s [22] and Mason et al.'s work [27]. Furthermore, fibers are likely to crack in the GDL when assembly force of the cell is large enough according to previous studies [28,29]. Unfortunately, the relationship between the electrical conductivity of the GDL and fiber microstructure has not been revealed, especially considering GDLs with various microstructures commonly used in the cell.

Thus far and to the best of our knowledge, studies of GDL electrical resistance remain insufficient. Since the GDL is a typical porous medium, the fiber microstructure in the material is highly sensitive to compression pressure, resulting in variation in the bulk resistance of the fuel cell. Various loading modes in the fuel cell, including steady load and dynamic load, may lead to different influences to the electrical resistance of the cell. Moreover, in terms of the fiber microstructure, three kinds of commercial GDLs are available on the market, including carbon paper, carbon cloth and carbon felt [30]. As shown in Fig. 1, the carbon fibers are distributed in a matrix (paper), woven (cloth) structure and hydro-entangled (felt) in these GDLs, respectively. According to Escribano et al. [31], the variation in the microstructure influences the properties of the GDLs. Therefore, two issues should be considered before the application of the GDLs, namely: how the bulk resistance and microstructure of the GDLs change with respect to the typical cyclic load and steady load of fuel cells, and what the difference is amongst the three types of GDLs due to various microstructure. It is necessary to understand the mechanism of correlation between the resistance and microstructure of typical GDLs under the compression stress.

Therefore, and in light of the aforementioned factors, the characterization of the cell with typical paper, cloth and felt GDLs is investigated and compared for the first time, showing that the resistance and microstructure are affected when subjected to various mechanical loads in this study. The remainder of the paper is organized as follows. The second section elaborates the experimental detail of the materials and resistance testing under two types of applied loads that are relevant to practical fuel cells. The accuracy of the measured results is discussed to illuminate the feasibility of the experiment. The third section describes the bulk resistance of the three GDLs, which are compared with the contact resistance obtained in the current literature. In the fourth section, the effect of cyclic and steady loads on the resistance is observed. Variation in the microstructure of different GDLs is observed to reveal the mechanism of the resistance change. In this study, the fiber microstructures in the typical GDLs are carefully observed and compared during the compression process of fuel cells. It is also helpful for enhancing our understanding of the changes in mass transfer behavior of fuel cells with various GDLs.

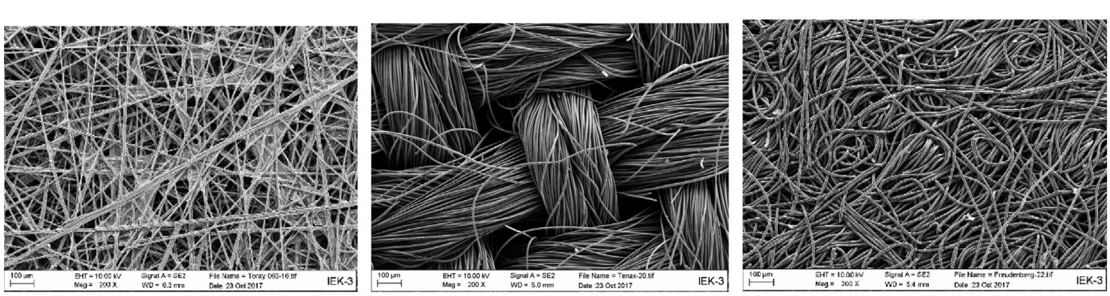
Table 1
Properties of GDLs used, as given by manufactures.

Manufacturer	Type	Initial thickness (μm)	Porosity	Fiber diameter (μm)
Toray	TGP-H-060	190	0.78	7–8
	TGP-H-090	280	0.78	7–8
Freudenberg	H2315	210	0.80 [34]	7–8
	H14	150	0.80 [34]	7–8
Toho Tenax	TCC 2660	260	–	10–11
	TCC 3250	320	–	10–11

2. Experimental detail

2.1. Material preparation

The most promising materials used in commercial GDLs, by virtue of their high porosity and excellent electric conductivity, are carbon-fiber based products [32]. In this study, GDLs with various microstructures, carbon paper, carbon felt and carbon cloth, were investigated and compared. Three typical untreated GDLs were obtained from the following manufacturers: Toray GDL (paper), Toho Tenax GDL (cloth), and Freudenberg GDL (felt).



(a) (b) (c)

Fig. 1. SEM images of (a) Toray carbon paper; (b) Tenax carbon cloth; and (c) Freudenberg carbon felt.