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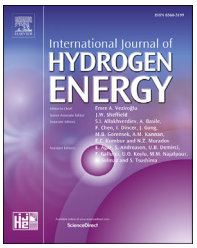

# Laser-perforated gas diffusion layer for promoting liquid water transport in a proton exchange membrane fuel cell

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ABSTRACT

A laser was used to perforate gas diffusion layer (GDL) that enhances liquid water transport from the electrodes to the gas channels. The generated holes diameter is from 80 to 200 μm, and center-to-center spacing is from 1 to 3 mm. A three-dimensional numerical model, based on a level set method, was built to investigate the water transport characteristics through the perforations with different diameters and spacing. Experiments and simulation results show that there is a better correlation among the diameter, spacing of the perforation and the power density. When the perforation diameter is 100 μm and the perforation pitch is 2 mm, the water transfer effect is the best which enhances the water discharge effectively and avoids the liquid droplets obstructing the gas flow channel at the same time. These results may assist in the design of GDL for water management in the operation of proton exchange membrane fuel cells.



## Introduction

Proton exchange membrane fuel cells (PEMFCs) have become a promising candidate for replacing fossil fuel fed engines in both stationary and mobile power sources, owing to their zero-emission characteristics, high efficiency, and power density. Nevertheless, effective water management is necessary in order to meet high fuel cell performance, reliability and durability. From a water management perspective, the gas diffusion layer (GDL) is a critical component, as it allows gas transport toward the catalyst layer (CL) and aids water vapor to reach the membrane increasing its ionic conductivity, while enabling capillary transport of liquid away from the electrodes to avoid severe performance losses caused by flooding [1–4]. Therefore, proper tailoring of GDL is critical to establish an optimal water management during PEMFC operation.

Various approaches have been developed to enhance water management in PEMFCs by tailoring the GDL. One of the most effective approaches is hydrophobic treatment by employing different hydrophobic agents, such as polytetrafluoroethylene (PTFE), polyvinylidene fluoride (PVDF), and fluorinated ethylene propylene (FEP) [5–7]. The hydrophobic

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agent is applied to the GDL in various ways: dipping, spraying and brushing, etc [8]. A majority of the efforts were performed to analyze the effects of PTFE loading and developing methods to optimize the ratio of hydrophobic [9–14]. It has been reported the carbon paper with propriety PTFE content reduces water saturation in the GDL, while higher content causes poor gas transport and high electronic resistance. In addition, the addition of a microporous layer (MPL) between the GDL and CL has been shown to enhance water management, resulting in the improvement in fuel cell performance [15–20]. In general, The MPL reduces contact resistance between the CL and the macroporous carbon substrate by forming flat and uniform layer that is not permeable to the catalyst particles.

Different from the previous method, a possibility to engineer the water transport within the GDL is based on artificially creating pathways for water removal, leaving the remaining regions free of water for improved gas diffusion. In the broad sense, previous approaches can be categorized into two groups: first, the approach of "local coating" is based on the application of a hydrophobic coating to defined regions, leaving the remaining (carbon fibers) uncoated. Cuenca et al. [21,22] have developed a method to produce GDLs with patterned wettability by means of the radiation grafting method. A material design consisting of defined patterned hydrophobic regions providing a dry transport pathway not limited by mass transport (decreased tortuosity) for reactant gases to reach the catalyst layer. Intermittent hydrophilic regions of the proposed material provide a separate pathway for product water to leave the cell. Second, the approach of perforation is using laser processing for adding perforations throughout the whole porous material, the approach was initially published by Gerteisenet al. and continued by other groups [23–26]. Manahan et al. [24,25] applied a dual-layer GDL (SGL 10BB, SGL group) with 100 μm and 300 mm laser-cut holes to the cathode compartment and quantitatively analyzed water mass through the MEA using neutron radiography testing.

Besides synchrotron radiography tomography to investigate the water transport in the perforated GDL, Alink et al. [26] was realizing high resolution visualization of water transport in laser perforated GDL using an ex-situ SEM setup. Markötter et al. [27] and Haußmann [28] investigated water transport in laser perforated GDL is by synchrotron radiography. In parallel with experimental studies, a number of studies based on numerical simulation have also been carried out, there have been studies investigating the liquid water transport in the PEMFC itself including the membrane electrode assembly (MEA) and the GDL and gas channel. However, few papers have attempted to numerical simulation droplets generated from the perforated GDL to the gas flow channel experimentally this dynamic behavior and its causes.

In this work, we seek to the optimal perforation diameter and center-to-center spacing by combining perforated carbon paper electrodes with a level set method to enhance performance of PEMFC and better understand the mass transport properties with respect to the two-phase flow of air and water. In addition, a detailed analysis and comparison of the system performance for MPL perforation and only GDL perforation electrodes was performed and the results are presented.

## Experimentals

### *Laser-perforation*

In order to determine the effects of hole size and spacing on the fuel cell performance, SGL 25 BCH Carbon Papers were perforated by using the HAN LASERY YLF-50, which operated under 20 W output power, 20 kHz frequency, and 1500 m/s marking speed. The perforations are located in the middle of the channel with diameters varying from 80 μm to 200 μm, and the spacing from 1 mm to 3 mm. The holes diameter and spacing parameters are listed in Fig. 1. In addition, a schematic of the laser perforation and the SEM images of different diameter holes are provided in Fig. 1.

### *Fuel cell and test station*

A parallel serpentine flow of 25 $cm^2$ single cell was used for the experiments. The perforated GDLs were attached to cathode side of the membrane electrode. The membrane electrode, using a Nafion membrane NR 211 (DuPont Inc., USA) as the electrolyte membrane, platinum loading were 0.45 $mg_{Pt}/cm^2$ Pt on the cathode side and 0.2 $mg_{Pt}/cm^2$ Pt on the anode side. The stoichiometric ratio of the hydrogen and air were fixed at 1.5 and 5.0 for the test conditions. Gases were fully humidified at 60 °C and a pressure of 1 atm was used for all the experiments.

## Simulation method

### *Theory model*

We employ level-set method to study the droplet movement process inside PEMFC gas channels. In the level set method, the level set function $\phi$ is usually defined as the signed distance function to the interface. The Level Set use a level set equation, a momentum transport equation and a continuity equation for the level set variable.

$$\frac{\partial \phi}{\partial t} + \mathbf{u}\cdot\nabla\phi = \gamma\nabla\cdot\left(-\phi(1-\phi)\frac{|\nabla\phi|}{\nabla\phi} + \varepsilon\nabla\phi\right) \quad (1)$$

$$\rho\frac{\partial \mathbf{u}}{\partial t} + \rho(\mathbf{u}\cdot\nabla)\mathbf{u} = \nabla\cdot\left[-p\mathbf{I} + \mu\left(\nabla\mathbf{u} + (\nabla\mathbf{u})^T\right)\right] + F_{st} \quad (2)$$

$$\nabla\cdot\mathbf{u} = 0 \quad (3)$$

In the level-set Eq. (1), the function $\phi$ is the range of 0–1. If $\phi < 0.5$, then it corresponds to phase 1; whereas $\phi > 0.5$, corresponds to phase 2; $\gamma$ and $\varepsilon$ are the stabilization parameters: $\varepsilon$ determines the thickness of the interface where $\phi$ goes smoothly from 0 to 1, and it should have the same order as the computational mesh size of the elements where interface propagates. The parameter $\gamma$ determines the amount of reinitialization of the level set function. A suitable value for $\gamma$ is the maximum value of the velocity field of u.

In Eq. (2), $\rho$ denotes density ($kg/m^3$), u velocity (m/s), t time (s), $\mu$ dynamic viscosity (Pa·s), p pressure (Pa), and $F_{st}$ the surface tension force ($N/m^3$).

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