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Feasibility study of using microfluidic platforms for visualizing bubble flows in electrolyzer gas diffusion layers

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HIGHLIGHTS

- Microfluidic platforms provide means to evaluate PEM electrolyzer GDLs.
- Experimental visualizations of two-phase flow in simulated GDL materials.
- Simulated GDL material properties extracted from computed tomography visualizations.

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ABSTRACT

In this study, microfluidic platforms were used to visualize air bubble transport in two-dimensional (2D) representations of gas diffusion layers (GDLs) to gain insight into how the geometric features of the GDL impact multiphase flow in polymer electrolyte membrane (PEM) electrolyzers. Two-dimensional porous networks were designed using volumetric pore space information, including average porosity and average throat size obtained from micro-computed tomography (micro CT) visualizations. Microfluidic chips were fabricated to represent felt, sintered powder, and foam GDLs and used to simulate the transfer of oxygen bubbles generated at the catalyst layer, through the GDL towards the flow channels of a PEM electrolyzer. The results of this work indicate that the use of microfluidic platforms for evaluating PEM electrolyzer GDLs is highly promising.

1. Introduction

The polymer electrolyte membrane (PEM) electrolyzer is a promising technology for producing hydrogen with higher purity and at higher pressure, compared to the competing alkaline electrolyzer [1–5]. Despite a significant increase in PEM electrolyzer research in recent years, there are few studies concerning transport phenomena [6,7]. In particular, the two-phase transport in the gas diffusion layer (GDL) of PEM electrolyzers has only recently been studied by Selamet et al. [6]. They investigated the two-phase flow in the GDL of a PEM electrolyzer by simultaneously using neutron radiography and optical imaging. They used a fine titanium mesh as the GDL, and they found that the water distribution was influenced by gravity and buoyancy forces. The authors also observed that oxygen gas saturation increased with increasing operating temperature.

Ito et al. [8] experimentally studied the effect of GDL pore properties, such as porosity and pore diameter on PEM electrolyzer performance. They observed that the electrolysis performance improved with decreasing pore diameter, while changes in porosity did not significantly affect the cell performance. Their experimental results showed that larger pores generated larger air bubbles that tended to block the water channels. This group also studied the effect of anode GDL properties on electrolysis by using titanium (Ti)-felt materials with various porosities and pore diameters [9]. Their results showed that gas bubbles hindered the water supply to the electrode, leading to increased concentration overpotentials. For small mean pore diameters the effect of decreasing the water

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supply on performance was limited, while concentration overpotential increased with increasing mean pore diameter of the anode GDL. Furthermore, they concluded that providing a uniform and suitable contact between the GDL and the catalyst layer reduced not only the contact resistance but also the activation overpotential. While these promising works have been valuable for the development of PEM electrolyzers, further research into the optimization of PEM electrolyzer GDLs is needed for increased efficiency and decreased hydrogen cost.

Direct visualization of two-phase transport in three-dimensional porous media such as the GDL can be challenging due to the opacity of the material [10]. One approach is to visualize two-phase flow in porous networks using microfluidic platforms [11–14], where a 2D representation of a porous media is used for simulating multi-phase flows. Using 2D porous networks to represent 3D porous media is widely used for investigating multiphase flows in areas such as oil and gas transfer in reservoir rocks [12,14–19] and water management in fuel cell GDLs [20–22]. Berejnov et al. [23] prototyped microfluidic networks and performed fluorescence based visualization to study multiphase transport phenomena in porous media. The authors demonstrated that wettability had a more significant influence on the saturation pattern than pore size distribution. Baouab et al. [14] studied the displacement of air injected into a porous medium saturated with oil and examined the effects of air and oil flow rates and oil viscosity on the displacement of oil. They found that at high oil flow rates and viscosities, air bubbles tended to break apart into smaller bubbles.

Typically, studies such as those described above concerning multi-phase flow in microfluidic chips did not employ pore networks with characteristics obtained directly from porous samples. Pore networks can be obtained from the analysis of high-resolution images [24]. Imaging porous media can be performed in a number of ways, such as micro CT [25–27], focused ion beam-scanning electron microscope (FIB-SEM) [12,25–27], and nuclear magnetic resonance (NMR) imaging [28,29]. Once the 3D reconstructed pore space of a porous medium is captured, the network of pores and throats and their geometrical information can be extracted using numerical methods such as a maximal ball algorithm [30,31], a medial axis algorithm [27,32,33], or a watershed algorithm [24,34]. Recently, Gunda et al. [12] performed waterflooding experiments by designing a microfluidic chip mimicking the porous structure of an oil reservoir rock. They used FIB-SEM to image the rock. Using reconstructed 3D images, the map of pores and throats were extracted. A 2D cross section of the 3D pore network was used to fabricate a 2D network on a microfluidic chip.

One challenging issue in PEM electrolyzers is the coverage of the catalyst layer by oxygen bubbles at the anode, which can hinder the transport of liquid water from the flow fields to the catalyst layer [9]. This mass transport limitation can lead to a decrease in the rate of hydrogen production. It is essential to employ a gas diffusion layer to facilitate the detachment of oxygen bubbles from the catalyst layer in order to reduce gas blockage and enhance the performance of PEM electrolyzers.

In this work, microfluidic platforms were designed and fabricated for the visualization of bubble transport in two-dimensional (2D) representations of three GDLs; felt, sintered powder, and foam. These 2D networks were constructed based on 3D micro-CT reconstructions, and were used to observe the growth, detachment, and propagation of air bubbles in a water-saturated porous medium and to determine the influence of the geometrical properties of the medium on bubble transport behavior. The microfluidic based investigations can be used to inform the design of new GDLs in order to improve electrolyzer efficiency.

There is a high potential for using microfluidic platforms to visualize and investigate two-phase transport in the GDL of PEM electrolyzers. To the best of our knowledge, this is the first use of microfluidic platforms for evaluating PEM electrolyzer GDLs.

2. Methodology

Micro CT technology was employed to image the GDL pore structure. Using a pore space extraction algorithm [24], the pore space information, namely porosity and throat size distributions, was extracted. This information was used to generate representative 2D networks and fabricate microfluidic chips.

Fig. 1 is a schematic of the microfluidic chip, which was used to simulate the two-phase flow of air and water in a PEM electrolyzer. The 2D porous medium was generated based on three-dimensional (3D) volumetric pore space information obtained from microscale computed tomography (micro CT) combined with image processing and pore extraction algorithms developed in-house. The volumetric pore space information obtained from micro CT imaging includes through-plane (across thickness of the material) porosity distributions and throat size distributions for each of the three GDLs. Our methods of micro CT imaging, calculating pore space information, generating representative networks, designing and fabricating microfluidic chips, and visualizing experiments are discussed in detail below.

2.1. Micro CT

Micro CT scans of three GDLs were obtained using SkyScan 1172 (a high-resolution micro-CT scanner; Bruker-micro CT, Belgium). A voltage of 100 kV and a current of 100 μA were used. A copper filter for removing low energy X-rays (noise) was used to improve the contrast between the titanium sample and the background. A sample size of approximately 6 mm × 3 mm was scanned for each of the GDLs. The height of the sample was limited by sample holder height (6 mm). It was also found that for a width greater than 3 mm, the noise level of the CT scan became prohibitive. The sample size used here was 18 times larger than the minimum sample size of 1 mm × 1 mm, recommended by Ref. [35] to obtain a repeatable porosity distribution. The pixel resolution was 2.88 μm per pixel.

The CT scans were reconstructed using NRECON software (SkyScan). Fiji (image processing software) [36], was then used to reslice the reconstructed greyscale images from the CT scan, in order to visualize the GDL from orthogonal through-plane and in-plane directions. Fig. 2 shows an example of a 3D image of the felt GDL.

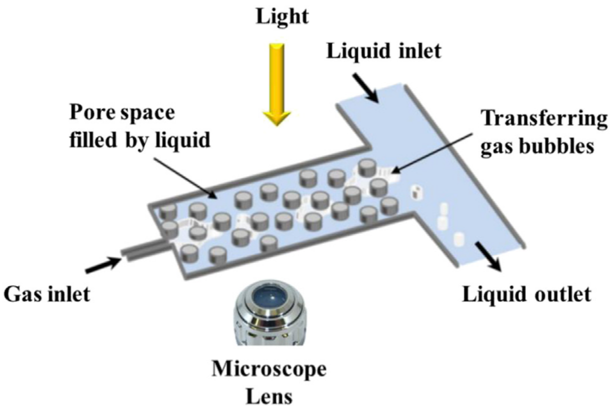

Fig. 1. Schematic of the microfluidic chip for bubble transport visualization. (Figure in colour available online.)