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ScienceDirect
Journal of Power Sources 170 (2007) 334–344
JOURNAL OF POWER SOURCES
www.elsevier.com/locate/jpowsour

Experimental investigation of liquid water formation and transport in a transparent single-serpentine PEM fuel cell

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Received 26 January 2007; received in revised form 30 March 2007; accepted 3 April 2007
Available online 18 April 2007

Abstract

Liquid water formation and transport were investigated by direct experimental visualization in an operational transparent single-serpentine PEM fuel cell. We examined the effectiveness of various gas diffusion layer (GDL) materials in removing water away from the cathode and through the flow field over a range of operating conditions. Complete polarization curves as well as time evolution studies after step changes in current draw were obtained with simultaneous liquid water visualization within the transparent cell. The level of cathode flow field flooding, under the same operating conditions and cell current, was recognized as a criterion for the water removal capacity of the GDL materials. When compared at the same current density (i.e. water production rate), higher amount of liquid water in the cathode channel indicated that water had been efficiently removed from the catalyst layer.

Visualization of the anode channel was used to investigate the influence of the microporous layer (MPL) on water transport. No liquid water was observed in the anode flow field unless cathode GDLs had an MPL. MPL on the cathode side creates a pressure barrier for water produced at the catalyst layer. Water is pushed across the membrane to the anode side, resulting in anode flow field flooding close to the H_2 exit.

Keywords: PEM fuel cell; Liquid water transport; Visualization; Gas diffusion layer; Microporous layer

1. Introduction

Humidification has to be carefully optimized in polymer electrolyte membrane fuel cells (PEMFC). Extremes in humidity levels at both the low end (membrane dehydration) and the high end (cathode flooding) of the range can significantly reduce PEMFC performance. Due to these conflicting requirements, the window for operating conditions for a PEMFC is very narrow. The cell is usually operated at the flooding limit, and some areas of the catalyst layer can be covered by condensing water. Since flooding has been identified as one of the main current-limiting processes, understanding and optimizing liquid water transport throughout the cell is critical to improving PEMFC performance. Moreover, flooding can also take place at lower current densities, if the gas flow rate and/or temperature (i.e. equilibrium vapor pressure) are low [1–3].

Various experimental techniques have been employed to investigate water dynamics in PEMFC. Membrane dehydration is commonly observed through the increase in the cell (i.e. membrane) resistance [1,6]. To detect cathode flooding, one can use *global* tools such as fully saturated air at the exit [1] and increase in the pressure drop [3,6,7]. Flooding is also associated with a drop in the cell output power. *Local* information about the flooded regions in the cell can be obtained by current and temperature distribution measurements [8]. Besides aforementioned physical indicators of flooding (current, temperature, pressure drop, and relative humidity), various *imaging techniques* can be used to investigate two-phase dynamics inside the cell. Known possibilities are direct flow visualization [7–10], neutron radiography [11], and magnetic resonance imaging [12].

Although direct flow visualization requires a special cell design (Fig. 1), it is a very attractive experimental technique since optical access to the channels provides high spatial and/or temporal resolution, depending on the combination of optics and recording equipment. Direct visualization offers the advantage of investigating two-phase phenomena at different length

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0378-7753/$ – see front matter
doi:10.1016/j.jpowsour.2007.04.020

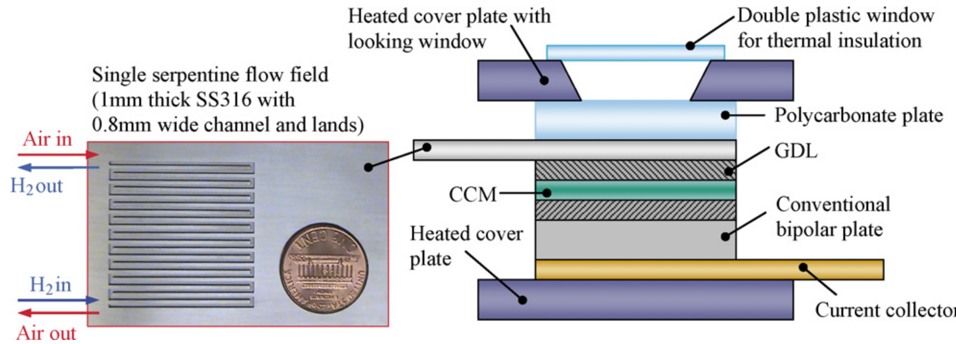

Fig. 1. Operational transparent PEMFC.

scales in an operating PEMFC environment, ranging from the cell/channel level [7,8], to the smaller scale level of the GDL pore/droplet [9,10], and down to the micro-scale level of water dynamics on the catalyst layer surface (recent work in our laboratory). Complete cathode flow fields with parallel channels were visualized in [7,8], with fields of view 6.5 mm × 62 mm, and 45 mm × 45 mm, respectively. Liquid water buildup was correlated with the increase in the pressure drop, while complete channel blockage was identified as the cause of the sharp prolonged decrease in current density at fixed voltage [7]. In addition, Tüber et al. [7] investigated the influence of the wetting property of the GDL on the cell performance and flooding, by modifying the standard Toray carbon paper TGP-H-90 to be strongly hydrophobic (20 wt.% PTFE) or hydrophilic. Optical imaging in [8] was used to provide complementary information about temperature and current distribution measurements. When water is in the vapor phase, higher temperature regions correspond to higher currents. Condensed water changes this correlation by lowering the current density in flooded areas, accompanied by local increase in temperature, attributed to the release of latent heat of condensation. Since the cells in [7,8] were not heated externally (ambient operating temperature and pressure), the investigation was limited to very low current densities (i.e. water production rates). Performance comparable to conventional cells, at higher operating temperatures of 70 and 80 °C, and 2 atm abs pressure, was reported in [9,10]. Wet-proofed Toray carbon paper TGP-H-90 (20 wt.% PTFE) with a microporous layer (MPL) was used as the GDL. Small portions of the parallel cathode flow field were visualized in order to investigate the droplet formation at the GDL/channel interface, followed by the droplet interactions with the channel walls. While such a small field of view (of the order of only a few millimeters) does not allow one to estimate the overall level of the flow field flooding, it enables one to observe micro-scale phenomena, such as repeatable droplet growth as water is wicked from the GDL through preferential openings at the GDL surface in the flow channel [9,10].

The visualization technique provides mainly qualitative data, as the top view of the channel typically does not offer depth perception. Since the thickness of water films, slugs and droplets often cannot be evaluated, it is very difficult (if not impossible) to quantitatively estimate the amount (volume) of water in the channels. Second, the transparency of water, coupled with highly reflective background comprised of GDL carbon fibers, represent obstacles for image processing. Estimation of the water volume has been achieved only at high magnification [9,10], and has been limited to the case when discrete droplets grow on the surface of the hydrophobic GDL. Droplet detachment diameter has been correlated with the mean gas velocity in the channel [10]. In spite of its qualitative nature, visualization has helped in understanding the influence of water dynamics on the cell performance.

The present work examines the two-phase flow inside a single-serpentine PEMFC by direct experimental visualization. Our approach is to correlate the overall flow field flooding and the cell performance, similar to the entire-cell visualization [7,8] of the parallel channels. While studies [7,8] were done at ambient temperature and low current densities (maximum around 0.25 A cm^{-2}), the present study investigates the flooding phenomena under realistic operating conditions at high water production rates (up to almost order of magnitude higher), with cell performance comparable to conventional cells. Second, previous studies used Toray TGP-H carbon paper: either standard [7,8] or modified in-house [7,9,10]. While Hakenjos et al. [8], Yang et al. [9], and Zhang et al. [10] did not investigate the influence of the GDL material, Tüber et al. [7] reported visualization results for GDLs with different wetting properties (untreated, hydrophobized, and hydrophilized Toray paper). The present work compares the performance of several commercially available GDL materials from three GDL manufacturers. In addition to Toray carbon paper, wet-proofed non-woven GDLs by SGL Carbon (both with and without the MPL), as well as the woven carbon cloth by Ballard, were tested in the serpentine cell. Our objective was to elucidate the influence of the GDL media on the cell performance through water management. An important distinction from the previous work is the investigation of the MPL influence on water management, through the visualization of the anode channel flooding. Experiments with conventional cells [13] and modeling efforts focusing on two-phase flow through the porous GDL [4,5] indicate that under certain operating conditions flooding may also be anticipated on the anode side, caused by the pressure barrier of the cathode MPL. This effect has not yet been investigated in detail, as the published work has insofar been limited to the visualization of the cathode side. The present study attempts to elucidate the water dynamics across the entire cell, by performing two series of visualization experiments, in