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The role of the gas diffusion layer on slug formation in gas flow channels of fuel cells

Thomas Hellstern, Eric Gauthier, May Jean Cheah, Jay B. Benziger*

Department of Chemical and Biological Engineering, Princeton University, Princeton, NJ 08544, USA

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ABSTRACT

Water drops emerge from large pores of the hydrophobic Gas Diffusion Layers (GDL) into the cathode gas flow channel of Polymer Electrolyte Membrane (PEM) Fuel Cells. The drops grow into slugs that span the cross-section of the flow channels. The slugs detach and are forced out the gas flow channel by the air flow. An acrylic micro-fluidic flow cell with a 1.6 mm gas flow channel and a 100 μm liquid pore through a carbon paper GDL has been used to quantitatively determine slug volumes, velocity of slug motion, and the force required to move slugs as functions of the gas and liquid flow rates. In a channel with 4 acrylic walls, slugs detach immediately upon formation. A porous GDL wall allows gas flow to bypass the slugs, thus allowing slugs to continue to grow after spanning the open area of the channel. The differential pressure to detach and move slugs is equal to the dynamic interfacial force on a slug normalized by the cross-sectional area of the channel. The dynamic interfacial force is equal to the difference between the downstream (advancing) and upstream (receding) contact lines of the water with the channel walls. Slugs will stop moving if the differential pressure drop for gas flow to bypass the slug and flow through the GDL under the rib separating the channels is less than the differential pressure required to move the slug. The results improve our physical insight into the state of water hold up in PEM fuel cells.

1. Introduction

Growing environmental concerns have pushed development of sustainable energy sources and hydrogen fuel is seen as a potentially viable source of clean energy production [1]. Polymer electrolyte membrane (PEM) fuel cells are likely to be an important electrochemical conversion device in the future energy landscape [2–5]. Water management is one of the biggest engineering challenges to the broader implementation of PEM fuel cells [6–15].

Water is produced at the PEM fuel cell cathode. The water produced at the catalyst layer pushes through the porous gas diffusion layer (GDL) to the gas flow channel. Water drops emerge from the GDL into the gas flow channels. The drops grow and are eventually detached and ejected from the gas flow channel. When the Reynolds' number for gas flow in the channel is small to moderate ($Re_G = (Q_G)/(w_{channel}\nu_G) < 20$; Q_G = volumetric gas flow rate, $w_{channel}$ = gas flow channel width and ν_G = kinematic gas viscosity) the emergent drops grow into slugs [16,17]. Slugs are drops that span the cross-sectional area of the gas flow channel [16,18,19]. When water drops and slugs are present in the gas flow channel, they can hinder reactant transport from the gas flow channel to the catalyst layer causing the local current density to decrease [9].

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* *Corresponding author*. Tel.: +1 609 258 5416; fax: +1 609 258 0211.
E-mail address: benziger@princeton.edu (J.B. Benziger).

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Liquid hindrance of gas flow is referred to as flooding, which can be alleviated by increasing the gas flow rate at the cathode. But high gas flow rates can dry out the membrane or necessitate increased energy input to humidify the feed gas; either scenario reduces the energy efficiency of the fuel cell [20–22].

To develop strategies to reduce flooding, we seek to understand the factors that affect the size of drops and slugs and their movement in the gas flow channels. There have been many experimental reports and computational fluid dynamic studies of multiphase flow in gas flow channels of fuel cells [10,12,23–38]. However, because of the complexity of the fuel cell construction it has been difficult to unambiguously determine the factors that control droplet/slug formation, detachment and motion. Two groups, Wu et al. [39] and Colosqui and Cheah [16,17], have introduced the use of microfluidic channels with a single pore entry to emulate the droplet emergence into a gas flow channel. Wu's work focused on droplet shedding which occurs at high gas flow rates that are encountered in large fuel cells with serpentine flow fields. Colosqui et al. focused on slug formation and motion that occurs at $Re_G < 20$ which is relevant for small fuel cells and fuel cells with parallel flow channels connected by common gas manifolds. Cheah et al. extended the introduced by Colosqui et al. to consider the effects of channel geometry, gravity and wettability of the channel walls on drop growth and slug formation at $Re_G < 20^{17}$, and has identified the conditions for drops to detach before slugs form [40].

The microfluidic flow channel employed by Colosqui et al. and later by Cheah had 4 acrylic walls permitting both video imaging as well as measurements of the differential gas pressure for flow through the channel during drop growth and motion. They focused on the steady periodic formation, detachment and ejection of water slugs from a gas flow channel at low to moderate gas phase Reynolds' number; $Re_G = 2Q_G\rho_G/w\mu_G$; where Q_G = volumetric gas flow, ρ_G = gas density, w = gas channel width and μ_G = gas viscosity [16,17].

In square and rectangular channels for $Re_G < 20$ drops grew via the sequence: (1) spherical caps grew above the water pore; (2) the spherical cap transitioned to a corner drop contacting the inlet pore and two adjacent channel walls; (3) the corner drop contacted a third side of the channel forming a partial liquid bridge; (4) the partial liquid bridge contacted the fourth wall of the channel forming slugs formed that spanned the cross-section of the gas flow channel. Cheah et al. found that the slugs formed in channels with both hydrophilic and hydrophobic walls. The force required to move slugs was almost independent of slug size, and scaled with the wetted perimeter of the contact lines of the slug with the channel walls, and the dynamic contact angles of water with the channel walls.

In a fuel cell gas flow channel three walls are solid and the fourth wall is the porous gas diffusion layer. The GDL will affect slug formation and motion in at least two ways: (1) the textured GDL surface is much more hydrophobic than smooth acrylic, teflon or any other solid material that would be used for the gas flow channels in a bipolar plate; and (2) the GDL is porous and gas flow can bypass liquid slugs in the gas flow channel by flowing through the GDL. The goal of this paper is to examine slug formation and motion in gas flow channels with a GDL layer present, and compare that to the previous results of Colosqui et al. and Cheah et al. where no GDL layer was present [16,17]. This study will examine slug formation at $Re_G < 20$ for square channels with three acrylic walls and the fourth wall being a GDL. Slug formation from both sessile and pendant drops is examined. Conditions of higher Re_G where drops detach before slugs form are considered in another paper [40].

2. Experimental

2.1. *Single channel flow*

The experimental setup was the same as that developed by Colosqui et al. [16]; it is shown schematically in Fig. 1. A 1.6 mm square channel in an acrylic block simulates the gas flow channel of a fuel cell. Gas is fed into the 125 mm long channel. A 100 μm diameter hole was drilled through the acrylic centered in the channel at a distance of 102 mm from the end of the channel. Water is fed to the 100 μm pore with a syringe pump. A 1.6 mm wide by 125 mm long strip by 0.37 mm thick of Toray carbon paper (TGP-H-120) with 20% Teflon loading was fixed with a thin film of silicon grease onto the channel wall with the water inlet. A fine gage needle was used to create a ∼100 μm diameter hole through the carbon paper aligned with the hole through the acrylic block. Nitrogen gas was flowed through the square channel with the gas flow rate controlled by a mass flow controller. Gas phase differential pressure, between the channel inlet and outlet, was obtained using a pressure transducer (Omega PX-160) and logged by computer at 20 Hz. A high speed camera (Phantom V5, Vision Research) recorded video images of the droplets and slugs in the channel.

The coordinate system for flow, shown in Fig. 1, is defined with respect to the water pore and the direction of gas flow. The x-axis is aligned with the direction of gas flow. The drops

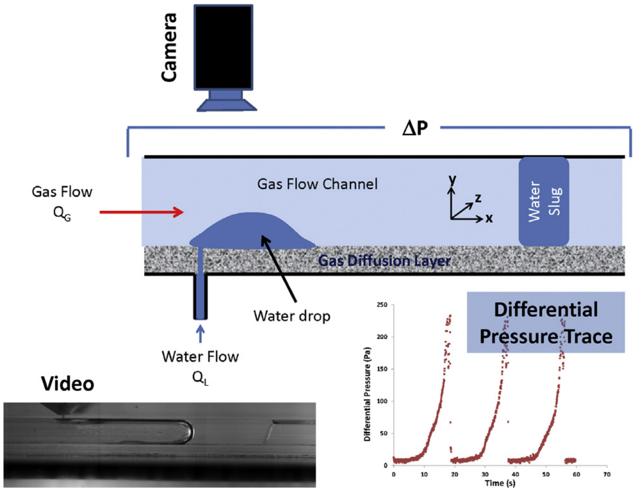

Fig. 1 – Schematic of the Experimental System. Gas flow was controlled by a mass flow controller and liquid flows were controlled by a syringe pump. Video images of the growing drops and moving slugs were time correlated with differential pressure measurements.