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Water emergence from the land region and water–sidewall interactions in Proton Exchange Membrane Fuel Cell gas channels with microgrooves

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HIGHLIGHTS

- Water–sidewall interactions in fuel cell channel corner region.
- Introduction of new channel wall designs-transverse grooved sidewalls.
- Comparison of plain and grooved channel walls on water transport dynamics.
- Pressure drop and visualization trends – along fuel cell channel length.

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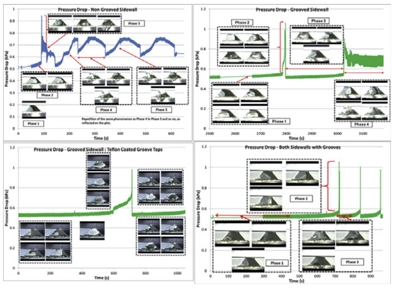
GRAPHICAL ABSTRACT



ABSTRACT

Liquid water produced in a Proton Exchange Membrane Fuel Cell (PEMFC) can adversely affect the fuel cell performance in two ways: (a) reduction in surface area available for reactant transport at the channel–gas diffusion layer (GDL) interface, and (b) increase in two-phase pressure drop in channels leading to flow maldistribution and increased pumping power. Further, the channels blocked by water reduce reactant availability at reaction sites. Most of the earlier water transport studies were focused on water droplet formation on the gas diffusion layer (GDL) in the channel and its removal from the gas flow without considering the sidewall interactions. In an actual fuel cell, water under the land emerges in the channel and fills the corner, drawing in additional water from the GDL surface. The present work explores water droplet–sidewall interactions and the transport of water from the corner region. Transverse micro-grooves are introduced on the sidewalls and their effect on water removal from the corner region, flow patterns, area coverage ratio and pressure drop are investigated. The micro-grooves are also seen to introduce a wetting regime that facilitates removal of water at the channel exit without causing blockage at the manifold region.

1. Introduction and literature review

Reactant gas supply channels play an important role in the working of PEM fuel cells. The gas channels bring the reactants to the GDL surface for transport to the reaction sites, and carry the product water out of the cell. Water emerging from the GDL surface

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into the channel has been studied extensively in literature, but the water emerging from under the lands in the channel corners has received very little attention in literature.

Previous work done by Kumbur et al. [1], Lu et al. [2], Cho et al. [3] and Polverino et al. [4] studied water being generated at the channel center along the flow axis. When water is injected at the channel center, the emerged droplet shape fluctuates with change in air flow rate. The droplet instability was found to be dependent on droplet size, channel size and the hydrophobicity of the GDL. A droplet is shown to grow and be removed due to air flow or transition into a film or a slug, which completely blocks the channel. However, these studies were limited to droplet–GDL interaction only and did not take into account the sidewall interactions.

Films are formed when a droplet grows in size and starts interacting with the sidewall. In one of the few studies on droplet–sidewall interactions, Theodorakakos et al. [5] in 2006 established that droplets are removed from the channel at slower velocities if they are also touching the sidewall and top wall. The reduced speed increases the resistance to flow of reactant gases and increases the pressure drop. Rath and Kandlikar [6] investigated the fundamental interactions between the water droplet and the sidewall and showed that the sidewall angle strongly impacts the water behavior. In 2012, Gopalan and Kandlikar [7] introduced air flow into the system investigated by Rath and Kandlikar. Gopalan and Kandlikar [7,8] also presented extensive work with trapezoidal channel angles and water droplet injection at channel center. They established that the 50° trapezoidal angle was the most suitable to avoid channel cross-section filling, which leads to slug flow and hence causes increased pressure drop.

Most of the previous research in this area has been focused on water droplet emerging at the channel center, neglecting the presence of water in channel corners and under the land. Schneider et al. [9,10] have done extensive in-situ work using segmented fuel cell flow fields. They measured local current densities in different parts of the flow-field and channel. Current density was found to be limited in the land region at higher voltages due to mass transport losses indicating difficulty in water removal from the GDL in the lateral direction underneath the land area. These findings are crucial and show that water generation under the land affects cell performance directly and water management in that cell region needs attention. Recently, Cheah et al. [11] analyzed spherical droplets transitioning into films and slugs. They discussed the interactions at a corner with Teflon coated sidewalls. Water was injected upstream and the shearing and ejection of water droplets were studied. They observed that droplets are ejected from the corner at a very high Reynolds number while films are shed at lower values of Reynolds number, suggesting formation of films can be beneficial in case of corner water droplet emergence.

Fundamental studies to identify corner droplet–sidewall interaction were conducted by Gopalan et al. [7] in 2012. They investigated effects of corner droplet injection in an ex-situ PEMFC channel. Fig. 1 shows the locations for droplet injection in a trapezoidal channel. It was found that when water was injected into the channel about 0.5 mm from the sidewall, the channel was filled with water for all air flow rates. The Concus-Finn [6,12] condition used for predicting droplet behavior between two surfaces fails to predict the behavior for corner droplet due to oscillatory nature of droplet interface.

Lee et al. [13] conducted experiments with rectangular channels and water injection at channel corners. They evaluated the effects of GDL wetting behavior on the droplet movement and pressure drop. A hydrophilic GDL caused the droplet to avoid corner filling and forced it to avoid sidewall contact. Effect of the sidewalls' wettability was suggested to have no effect on water behavior in their work. The effect of hydrophilic, hydrophobic and uncoated channel sidewalls with hydrophobic GDL on two-phase pressure drop and water flow patterns was discussed by Lu et al. [2] and no clear trend regarding the channel wettability that causes low two-phase pressure drop could be identified.

Droplet interactions on a grooved surface have been investigated in literature [14–21] which discussed selective water droplet drainage or retention. Sommers et al. [14] compared droplet velocity for different liquids on plain and grooved surfaces. Droplets had a higher velocity on grooved surfaces than over a plain surface. Chen et al. [21] concluded that surface roughness amplifies the water repellency of surfaces. Rahman et al. [15] discussed the effect of droplet shape on water drainage from a grooved surface and the effect of geometrical parameters like groove depth, pillar width and a factor known as solid fraction, $=W_P/(W_P + D_G)$, where W_P is groove pillar width and D_G is groove depth. They indicated that in order to easily remove water from a grooved surface, the surface should be designed such that the groove width to pillar width ratio is >0.2 (reciprocal of Scaling Factor developed by Nosonovsky et al. [18]) and at the same time, the pillar width should be limited as the solid fraction increases both strength of droplet pinning and sliding angle for removal.

Gopalan et al. [22] studied different grooved surfaces and their static wetting behavior. This included the Cassie–Baxter, Wenzel and metastable [23–25] wetting regimes. In this work, rectangular grooves on PEMFC gas channel sidewalls were proposed. These grooves were targeted at enhancing removal of water injected at the channel corner or emerging from under the land. Further investigation of the grooved surfaces for directional wettability included a study by Wang et al. [26], who presented a detailed discussion about the individual and combined wetting due to micro-grooves having Cassie and Wenzel roughness. They noted that the wetting regimes observed under static conditions may not hold true during dynamic water flow over the grooves and that is when it tends to possess both wetting regimes simultaneously. It was established in case of metallic grooved surfaces that drops in Wenzel wetting state are more elongated (films) than Cassie–Baxter wetting state under dynamic conditions. These findings confirmed to a certain extent that grooved sidewalls can help improve water management in a PEMFC gas channel.

The slugs formed in a PEMFC channel and its dynamics are affected by the gas bypassing through the GDL. Slugs can divert the gas flow through the gas diffusion layer (GDL) beneath the channel ribs to adjacent channels in a channel flow field with multiple channels. This study is limited to a single channel. This flow diversion can cause slug motion to slow down or come to a halt [27,28]. Ye et al. [27] explain in their paper that the gas pressure drop required to overcome slugs is independent of the slug volume. In this work, different water features have been observed along with slugs. For the cases with slugs, the gas bypass will affect the pressure drop results, but its effect is expected to be negligible.

2. Objectives of the present work

Considerable work has been done on single water droplet behavior in a cell channel; however, not enough studies include the effect of sidewall interactions. Earlier work on droplet behavior on grooved surfaces by Gopalan and Kandlikar [22] show that water droplet movement and droplet shape is significantly affected by the presence of grooves. In this study, grooves on the sidewalls are considered for water droplet movement away from the channel corner. The implementation of grooved sidewalls targets at promoting film flow behavior while avoiding channel cross-section blockage by slugs. At the same time, these water films are expected to cling more to the channel sidewalls and top wall rather than to the GDL surface. An experimental study is undertaken to