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Effect of channel materials and trapezoidal corner angles on emerging droplet behavior in Proton Exchange Membrane Fuel Cell gas channels

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HIGHLIGHTS

- Experiments conducted to understand droplet behavior in a trapezoid gas channel.
- At lower air velocities droplet showed corner filling and non-filling behavior.
- At higher air velocities the droplet slid off from the GDL without touching the channel walls.
- Developed model to predict minimum velocity required to remove droplet from channel.
- Model extended to predict ΔP required for corner filling and non-filling cases.

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ABSTRACT

Ex situ experiments were conducted to study water droplet dynamics in Proton Exchange Membrane Fuel Cell (PEMFC) gas channels with different trapezoid channel open angles and GDL materials under controlled air velocities (0.48–7.23 m s^{-1}). High speed videos revealed that the droplets interacted with the channel walls at lower air velocities (0.48–4 m s^{-1}) and led to channel corner filling depending on the channel open angle. However, at higher air velocities (4.1–7.23 m s^{-1}), the droplets did not contact the channel walls and slid off from the GDL surface. For higher air velocities, a correlation was obtained for the minimum velocity required to remove the droplet from the channel without interacting with the channel walls. For lower air velocities, the minimum pressure drop required for removing the droplet from the gas channel for both corner filling and non-filling scenarios was obtained. The study clearly establishes the important role played by the channel sidewalls and the channel angle on the water droplet transport characteristics.

1. Introduction

Water management in Proton Exchange Membrane Fuel Cells (PEMFCs) has been receiving attention in the automotive sector over the past few years [1–14]. The water removal is particularly challenging at lower gas velocities encountered in the channels during startup and shutdown cycles since the gas velocity is low during these periods. This makes the liquid water removal difficult [1]. Removal of water droplets from the gas channel effectively without lowering the fuel cell efficiency is one of the major issues that needs to be addressed before commercialization of the PEMFCs become a reality in the automotive industry [2].

Over the past few years, a lot of research has been done to address the efficient water removal from the gas channels of the PEMFCs. It has been reported that various factors such as air velocity, channel wall and gas diffusion layer (GDL) material properties, contact angle hysteresis on the GDL and the channel walls, droplet emergence location, and channel cross sectional geometry play important roles in the water removal process [1–23]. It was also revealed that the air flow in the channel exerts pressure force on the droplet which in turn deforms the droplet by changing its contact angle on the channel surface and eventually leads to its removal [9–12].

A droplet or a slug (elongated droplet touching the sidewalls) experiences different forces that act on it and determine its

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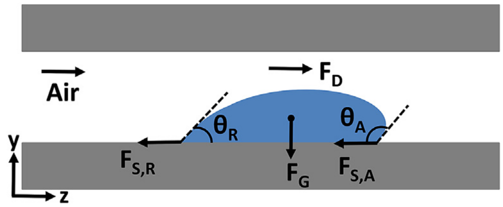

Fig. 1. Different forces acting on the droplet in the PEMFC gas channel.

movement in the gas channel. Fig. 1 shows the different forces acting on a droplet which include gravity (F_g), surface tension ($F\gamma$) and the drag force (F_D) applied due to the gas flow in the channel [24,25]. It is seen that the droplet moves in the gas channel when the gravity and the drag forces overcome the surface tension force holding the droplet in the channel.

The effect of gravity on the droplet (or slug) depends on the size of the droplet. This is generally governed by the Bond number ($B_o = \rho g D^2/\gamma$), which is the ratio of the gravity force to the surface tension force. It is reported that if $B_o \sim 0.1$ or lower, the surface tension forces are dominant in the system and the gravity forces can be neglected [3,26]. Since, the channel size used for gas channels is smaller than about 1 mm, the droplet sizes in the channel are also quite small. Hence, most of the studies in PEMFCs neglect the gravity effect on the droplet. However, it is also seen from a few studies that the gravity does have an effect on the droplet in the PEMFC gas channel [13,22,24,27–29].

Kimball et al. performed a study to understand the effect of gravity on the water movement in the gas channel [24]. They mentioned that the motion of the slug in the gas channel is gravity dependent when the fuel cell is placed vertically. The reactant gas channels are blocked and the current density fluctuates when the slug has to move against the gravity. They also found that the gravity effects were amplified when the large pore for droplet emergence was under the channel region. However, when the large pore was under the land region, the gravity effects diminished [27]. Yi et al. also studied the effect of gravity on the fuel cell performance and concluded that at an optimized gravitational angle for cell orientation, the output power of PEMFC stack can be enhanced greatly [28]. Chen and Wu studied the effect of gravity on water discharge in the PEMFC gas channel [29]. They concluded that the excess water present in the cathode channel is easily removed from the cell when the anode channel orientation is upwards. They also suggested that the placement of anode and cathode is very important for the performance of the PEMFC. Lu et al. studied the effect of orientation of the cell on the water distribution and flow patterns in the gas channels and also found that the vertical orientation of the cell was beneficial for the water flow pattern and the two phase flow in the gas channels as compared to the horizontal cell [22]. Das et al. studied the effect of adhesion force on the liquid water removal from the GDL [13]. They reported that for droplets smaller than 1.5 mm in diameter, the gravity effect can be neglected. However, when the droplet size is above 2 mm or B_o is above 0.14, the gravity has a significant effect on its removal. Therefore, it can be concluded from these studies that the gravity effect in the PEMFC gas channel can be neglected only when the droplet diameter is smaller than 1 mm or B_o less than 0.1, otherwise it needs to be considered in the analysis.

The surface tension forces also play a major role in the droplet removal process. The adhesion force exerted by the surface tension on the droplet is a function of the surface wettability defined by the contact angles (θ) and the contact angle hysteresis ($\Delta\theta$) [30]. Contact angle hysteresis is the difference between the advancing (θ_A) and the receding (θ_R) contact angles. θ_A and θ_R are the maximum and the minimum contact angles respectively that the droplet makes on a surface before it begins to travel on or depart from the surface. When the hysteresis $\Delta\theta$ of a material is high, a larger drag force is required from the air flow in the channel to remove the droplet. When a droplet interface has an angle $\theta < 90°$, it is called a hydrophilic surface and the liquid would spread. An interface having $\theta > 90°$, known as hydrophobic surface, the liquid repels the surface and tries to attain a spherical shape. Droplet removal from a hydrophobic surface is easier as the force required to remove the droplet is less compared to a hydrophilic surface for a given hysteresis. GDL being a hydrophobic surface allows droplet removal relatively easily compared to the hydrophilic channel surface.

Earlier works reported in this area indicate that material properties of the channel sidewall have great influence on the water transport in the gas channel [22,31–34]. It is seen that even though the water moved faster on a hydrophobic surface, having a hydrophobic channel sidewalls is disadvantageous for gas diffusion to the catalyst layer and the fuel cell performance [31]. Quan and Lai performed a numerical simulation to understand water management in the gas channels and found that the hydrophilic channel surface facilitates the transport of reactant gases to the reaction sites by transporting the water along the channel edges [32]. This acts as an effective water management strategy in the gas channels. On the other hand, hydrophilic surface also increases the pressure drop due to liquid water spreading, forming slugs and leading to blockages in the channels. Zhu et al. conducted a numerical study to understand the effect of surface wettability on the droplet removal from the gas channels [33]. They proposed that the hydrophilic channel walls spread water to the channel corners leading to film flow and eventually result in blocking of the gas flow pathways. Similar experimental study was performed by Lu et al. and they found that the hydrophilic channels help in uniform water distribution along the GDL surface [22]. They also stated that hydrophilic gas channel walls help in creating film flow in the channel and therefore reduce the pressure drop in the channel. From all these work it could be seen that both hydrophilic and hydrophobic channels have their merits and demerits.

It was also noted that the channel geometry has an important effect on water management in the PEMFC gas channels. Owejan et al. performed an *in situ* study to understand the effect of gas channel properties on water accumulation in the PEMFCs [15]. They stated that triangular cross-sectional channels retained less amount of water compared to rectangular channels at a given current density. Zhu et al. performed a numerical investigation on six different channel geometries to understand which geometry performs better for a PEMFC gas channel [34]. It was observed that the detachment time, detachment diameter, and removal time of water droplets were found to be lower for triangular and trapezoid channels, and higher for rectangular and upside down trapezoid channels. Similar study was performed by Lu et al., and they reported that sinusoidal and trapezoidal channels produce lower pressure drops in the channel compared to rectangular gas channels [22].

Rath and Kandlikar performed *ex situ* experiments to understand how different angled trapezoid channels affect the droplet dynamics in gas channels from a microscopic perspective [23]. They found that the droplet wicking into the channel corners for a trapezoidal channel depends upon the Concus-Finn condition. According to Concus-Finn condition,

$$2\alpha \le (\theta_B + \theta_W) - \Pi \quad (1)$$

where θ_B and θ_W is the contact angle for the base and the wall surfaces respectively, and *2α* is the channel open angle (angle between the sidewall and GDL) [35–37]. If this equation is satisfied