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Emergence of droplets from a bundle of tubes into a micro-channel gas stream: Application to the two-phase dynamics in the cathode of proton exchange membrane fuel cell

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ABSTRACT

Understanding the coupled two-phase dynamics in the cathode gas diffusion layer (GDL) and gas channel (GC) is of vital importance to optimize water management and to improve performance of proton exchange membrane fuel cell (PEMFC). However, it is difficult to directly observe the two-phase flow in the cathode of PEMFC because the GDL is opaque and has complex structures. To circumvent this issue, a similarity experiment model is developed in the present study. Based on the soft lithography technology, we fabricate a microfluidic device composed of a duct representing the GC and a bundle of tubes representing the GDL. Emergence of liquid droplets from these tubes into the duct gas stream is conducted to mimic the two-phase dynamics in the GDL and the GC. With this similarity experiment, we explore the influences of the gas flow rate on the liquid water flow in the cathode of PEMFC as well as the effects of the GDL surface defects on the two-phase dynamics in the GC. The two-phase flows in the hydrophilic and hydrophobic systems are also compared to elucidate the effects of wettability on water management of PEMFCs.

1. Introduction

In the present scenario of a global quest towards a clean and sustainable energy future, fuel cells are widely considered as 21st century energy-conversion devices for automotive, stationary, and portable power because of their high efficiency, environmental friendliness, and minimal noise. Among various fuel cells, proton exchange membrane fuel cell (PEMFC) is regarded as one of the most promising power sources for a wide range of applications. A typical PEMFC consists of a proton exchange membrane sandwiched between two electrodes (anode and cathode), each of which includes a bipolar plate with grooved gas channels (GCs), a gas diffusion layer (GDL), and a catalyst layer (CL), Fig. 1. At the anode CL, hydrogen dissociates into protons and electrons, which then pass to the cathode CL through the membrane and an external circuit, respectively. At the same time, oxygen in the cathode CL reacts with protons and electrons from the anode to produce heat and water. Therefore, the overall reaction is simply hydrogen reacting with oxygen to produce electrical energy, heat, and water, without any pollutants.

Water plays a vital role in performance and durability of PEMFC. In the cathode CL, the continuously generated water is prone to condense to form liquid water, since PEMFC usually operates at about 80 °C On the other hand, the produced water in the cathode CL also can be absorbed into the membrane to make it swell. This membrane swelling in turn pushes liquid in the cathode CL to penetrate into the GDL and emerge into the GC, which is then removed by incoming reactant gas, as schematically illustrated in Fig. 1. Obviously, liquid in the GDL and GC impedes transport of reactant gas to the reaction sites. Therefore, to improve fuel cell performance, the liquid removal techniques must be optimized. To do this, it is needed to understand deeply the two-phase flow processes in the cathode of PEMFC. Extensive effort has been made on this direction during the past two decades. However, most of the studies are focused on the two-phase flow either only in the GDL or only in the GC [1–7]. Little light is shed on the coupled two-phase transport processes in the GDL and the GC. It is expected that two-phase dynamics in the GDL and the GC interact with each other. For instance, the liquid transport process in the GDL determines the location where liquid enters the GC; on the other hand, the two-phase dynamics in the GC alter the pressure filed therein, which in turn affects the liquid flow in the GDL. However, it is difficult to directly observe the coupled two-phase flow

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Nomenclature

A	active area (6.5×10^{-7} m^2)
Bo	Bond number
Ca	capillary number
d	pore width (μm)
D	characteristic length (450 μm)
e	pore depth (50 μm)
F	Faraday's constant (96458 C mol^{-1})
g	gravitational acceleration (9.8 m s^{-2})
i	current density (A m^{-2})
M	molecular weight of liquid water (0.018 kg mol^{-1})
P_l	pressure in liquid phase (Pa)
P_g	pressure in gas phase (Pa)
P_t	flow resistance (Pa)
Q_l	liquid flow rate (50 μl h^{-1})
Re	Reynolds number
t^*	time (s)

Greek symbols

α	net drag coefficient
θ	contact angle between gas/liquid interface and gas/solid interface
θ_{nm}	contact angle taken in non-wetting phase
θ_a	advancing contact angle
θ_r	receding contact angle
ϕ	aspect ratio
μ	dynamic viscosity of liquid water (3.5×10^{-4} Pa s)
σ	surface tension (0.0625 N m^{-1})
τ_{ls}	surface tension of liquid/solid interface (N m^{-1})
τ_{gs}	surface tension of gas/solid interface (N m^{-1})
τ_{gl}	surface tension of gas/liquid interface (N m^{-1})
ρ	density of liquid water (1000 kg m^{-3})

in the GDL and the GC of a running PEMFC, since the GDL is opaque and has complex structures. In the present work, we propose to circumvent this issue using the similarity experiment approach.

Several ex-situ experimental studies have been tried to disclose the coupled two-phase flow in the cathode of PEMFC. Bazylak et al. [8] investigated the dynamics of liquid transport through a GDL and then into a GC. It was revealed that the droplet emergence/detachment regime is followed by a transition into a slug formation regime; during this regime, droplets tend to pin near the breakthrough location. Droplets emerge from the GDL at preferential breakthrough locations; but these breakthrough locations change intermittently, indicating that removal of liquid in the GC alters the liquid flow in the GDL. Lu et al. [9] experimentally investigated liquid breakthrough dynamics in the GDLs with and without a micro-porous layer (MPL). Recurrent breakthroughs are observed for all the GDL samples. For the GDLs without a MPL, a dynamic change of breakthrough locations is observed, whereas this is not found in the GDLs with a MPL. The authors also found that the MPL has a great effect on the two-phase dynamics in the GC. As compared to the GDLs with a MPL, the GDLs without a MPL can promote the film flow and shift the slug-to-film flow transition to a lower air flow rate. Obviously, the presence of the MPL alters the liquid flow in the GDL. That is to say, the two-phase dynamics in the GC depend on the liquid transport process in the GDL. These ex situ experimental studies have showed that the two-phase flow in the GDL and GC have a strong interaction with each other. Nevertheless, owing to the opaque characteristics of the GDL, the two-phase flow in the GDL is not elucidated in these works.

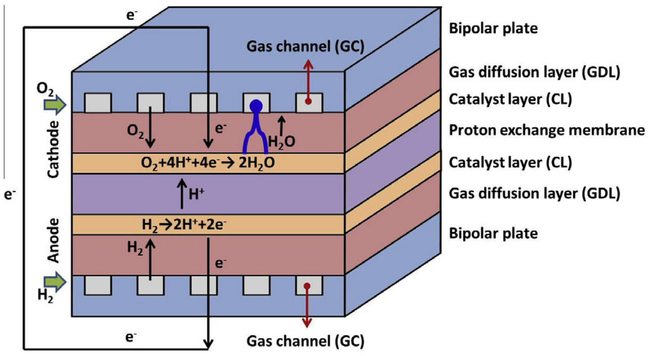

Fig. 1. Schematic diagram of PEMFC as well as the transport and reaction processes.

In addition to the ex-situ investigations, some in situ experimental studies have also been carried out to understand the coupled two-phase dynamics in the cathode of PEMFC. Manke et al. [10] employed the high-resolution synchrotron X-ray radiography techniques to investigate liquid evolution and transport in an operating fuel cell at the microscopic level. The authors found that the mode of liquid transport varies between different locations in the fuel cell. In some spots, a continuous flow of liquid is observed, while an eruptive transport mechanism is revealed in others (eruptive transport is that the liquid droplets in the GDL are ejected into the GC and merge into a single droplet in a short period). The behavior of this eruption is periodic with an almost constant frequency and always takes place in approximately the same pores in the GDL. Harning et al. [11] also used this synchrotron X-ray radiography method to elucidate the two-phase dynamics in PEMFC. Liquid transport in the GDL can be described by consecutive Haines jumps; and the small liquid clusters in the GDL merge to form larger ones, which finally burst from the GDL to the GC. During this burst process, the bursting liquid droplet carries away liquid from the GDL and the 'supply' is not sufficient to fill the pores, making these pores to be empty. These empty pores are filled afterwards, and the cycle starts again. Although the liquid burst phenomenon is clearly captured in these experiments, the interactions between the two-phase flow in the GDL and the GC is not disclosed, mainly owing to limitation of the current visualization technologies and the complex three-dimensional GDL structures.

In parallel to the experimental studies mentioned above, some researchers have also employed the numerical simulations to understand the coupled two-phase dynamics in the cathode of PEMFC. Esposito et al. [12] developed an accurate and computationally fast model for coupled two-phase flow in PEMFC. The liquid flow in the GDL is described by Darcy's law, and droplet transport at the GDL/GC interface is achieved through a simplified phenomenological description, which considers the droplet formation, growth, coalescence, and detachment. However, the interactions between the liquid flow in the GDL and the GC cannot be disclosed by this model. Moreover, this macroscopic model cannot reveal the detailed pore scale transport process in the GDL.

To gain deep understanding of the coupled two-phase dynamics in the cathode of PEMFC, pore scale simulations have also been performed. Tabe et al. [13] used the lattice Boltzmann (LB) method