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Evaluation of self-water-removal in a dead-ended proton exchange membrane fuel cell

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HIGHLIGHTS

- Operation characteristics in a dead-ended PEM fuel cell were addressed.
- Modified flow channel was used to realize water removal.
- A novel method by condensing the moisture in the stack end was introduced.

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ABSTRACT

In this paper, the operation characteristic of a dead-ended proton exchange membrane fuel cell (PEMFC) placed with vertical orientation is investigated. The relationship between the channel geometry and the wettability of the gas diffusion layer (GDL) surface is theoretically analyzed. Based on the theoretical analysis, straight flow channels with 2.0 mm width and 1.0 mm depth are used for the experimental investigation and the moisture is condensed at the stack end to improve water removal. The results show that the designed fuel cell can operate for about 1 h at 800 mA cm^{-2} and the performance of the cell decreases with the increase in the operation temperature. Moreover, the recovered liquid water is corresponded closely to the theoretical values.

1. Introduction

Proton exchange membrane fuel cell (PEMFC) has been considered to be the main substitution of power source for automotives, steady power stations, and submarines due to its high energy conversion efficiency, high power density, quick startup, and low environment pollution [1–21]. Restricted by current formation and proton transportation mechanisms, liquid water generally exists in PEMFC during its operation. Thus, water management is of great importance for PEMFC [22–24]. Liquid water present in the cathode catalyst layer can reduce the accessibility of oxygen to the reaction sites and can possibly lead to flooding in the catalyst layer, gas diffusion layer (GDL), and gas flow channels, especially at high current densities [25]. Understanding and improving liquid water removal throughout the cell are critical in improving PEMFC performance. Many studies have focused on the improvement of water management. Ous and Arcoumanis [26] designed a transparent fuel cell to investigate the simultaneous water droplets characteristics in a serpentine flow channel, and the visualization images showed that the flow channel was blocked by the overlapping of two land-touching droplets and air flow was the most crucial issue to the flooding among the test operating conditions. Owejan et al. [27] used neutron radiography method to investigate the effects of flow field and diffusion layer properties on water accumulation in 50 cm^2 fuel cells. It was found that cells constructed using diffusion media with lower in-plane gas permeability tended to retain less water and flooding within the electrode layer or at the electrode-diffusion media interface was the primary cause of the significant mass transport voltage loss. Li et al. [28] designed novel bipolar plates based on the determination of an appropriate pressure drop along the flow channel, which could effectively remove water from cells. With their design, no liquid water was observed to flow out of the cell at the anode and cathode channel during the performance tests as confirmed by the neutron imaging technique. Zhu et al. [29,30] investigated the dynamic behavior of liquid water emerging from a GDL pore into a gas flow channel and water droplet dynamics in the gas channel by two-dimensional and three-dimensional numerical simulations, respectively. It was found that the critical velocity decreases with increasing droplet size and

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Nomenclature

f	hysteresis force (N)
σ	liquid–gas surface tension (N m^{-1})
R_c	bottom radius (m)
θ_A	advancing angle (°)
θ_R	receding angle (°)
θ	Young's contact angel (°)
V	droplet coronal volume (m^3)
ρ	liquid water density (kg m^{-3})
g	gravity acceleration (m s^{-2})
I	current (A)
F	faraday constant (C mol^{-1})
M_{H_2O}	molar weight of water (kg mol^{-1})
$\dot{m}_{H_2O}$	water generated rate (kg s^{-1})
$\dot{m}$	mass flow rate of liquid water (kg s^{-1})
Q	heat due to phase change (W)
Q_{re}	heat removal by coolant water (W)
h_{fg}	latent heat of water vapor (J kg^{-1})
C	specific heat liquid water (J kg^{-1} °C^{-1})
T_{out}	outlet temperature of the coolant water (°C)
T_{in}	inlet temperature of the coolant water (°C)
ΔT	temperature difference of the coolant water (°C)

decreasing GDL pore diameter and the wettability of the microchannel surface had a major impact on the dynamics of the water droplet removal. Lu et al. [22] pointed out that channel surface wettability, geometry and orientation were important issues regarding to the water management in PEMFC, and horizontal channel orientation was more prone to slug flow, non-uniform liquid water distribution and instable operation than vertical channel orientation. Based on the previous research, Jiao and Li [31] pointed out that the sliding angle played an important role in the water droplet removal in PEMFC, and the surface dynamic wettability of GDL had significant effect on liquid water transportation. Litster et al. [32] used a porous carbon flow field plate as an integrated wick to redistribute water within the fuel cell, and an external electro-osmotic pump was introduced to remove excess water from the channels and gas diffusion layer. Metz et al. [33] presented a passive water removal by capillary droplet actuation with a triangular micro-channel. Lai et al. [34] investigated the wettability of coated metal bipolar plates in the water removal property.

Most literature works related to water removal in PEMFC have mainly focused on open-ended H_2/air PEMFCs, and there were also a substantial amount of work on water management in dead-ended anode arrangements in H_2/air PEMFCs [35–38]. However, H_2/O_2 PEMFC is also important in special applications, which require both hydrogen and oxygen dead-ended operation. As a consequence, water removal became more complicated in this situation. Mocoteguy et al. [39] investigated a five cells H_2/O_2 stack with dead-ended both experimentally and by simulation. The performance of the cell decreased immediately, and the operation time was less than 60 s. They pointed out that liquid water generated in the cell resulted in the starving of the active layer with oxygen, and water management, especially liquid water removal, was very important for a dead-ended PEM fuel cell. Gas circulation might be helpful for the water removal. However, Pien et al. [40] pointed out that gas circulation pump was not desirable in this kind of cell due to the potential fire hazards associated with fast moving mechanical components in the pure oxygen atmosphere in despite of the lines were oil-free or not, and purging procedure would also be up against the potential fire hazards due to the fatigue loss on the membrane caused by the pressure concussion.

In this paper, a modified flow channel on the flow field plate was expected to realize the water removal in a dead-ended H_2/O_2 PEMFC. The relationship between the channel geometry and the wettability of the GDL surface were theoretically investigated and a novel method to enhance the water removal ability was introduced by condensing the moisture at the stack end.

2. Theoretical framework

The liquid water droplet is formed on the GDL surface by accumulation of water flowing out the GDL through the pores in PEMFC. With the growth of droplet, they could finally clog the flow channel [41]. Therefore, it is necessary to remove the droplet before gathering. Furmidge [42] and David et al. [43] pointed out that the threshold resistance which the droplet movement needed to overcome, seen in Fig. 1a, could be calculated from the following equation:

$$f = \pi\sigma R_c(\cos\,\theta_R - \cos\,\theta_A) \tag{1}$$

where R_c is the bottom radius of the droplet coronal, σ is the liquid–gas surface tension, θ_A and θ_R are the advancing and receding angles of the droplet, respectively. Wang et al. [44] analyzed the mechanical equilibrium of the drop on the rough surface related to the contact angle hysteresis and deduced that in the critical state, the relations of θ_A, θ_R and the Young's contact angel θ could be expressed as

$$\cos\,\theta = \frac{\cos\,\theta_A + \cos\,\theta_R}{2} \tag{2}$$

The volume of the droplet coronal can be expressed as,

$$V = \frac{1}{3}\pi R_c^3\frac{(1-\cos\,\theta)^2(2+\cos\,\theta)}{\sin^3\,\theta} \tag{3}$$

Consequently, droplet removal with the present of gravity requires

$$\frac{1}{3}\pi\rho g R_c^3\frac{(1-\cos\,\theta)^2(2+\cos\,\theta)}{\sin^3\,\theta} \geqslant \pi\sigma R_c(\cos\,\theta_R - \cos\,\theta_A) \tag{4}$$

where ρ is the density of the droplet, g is the gravity acceleration, the items on the left and right are gravity and hysteresis force, respectively. To simplify the calculation, the critical value of θ_R and θ_A for a liquid drop on an inclined PTFE surface can be shown as follow [45]:

$$\frac{\theta_A - \theta_R}{\theta_A} = 0.2 \tag{5}$$

Therefore, combining Eqs. (2), (4), and (5), the detachment radius for a specific contact angle can be expressed as:

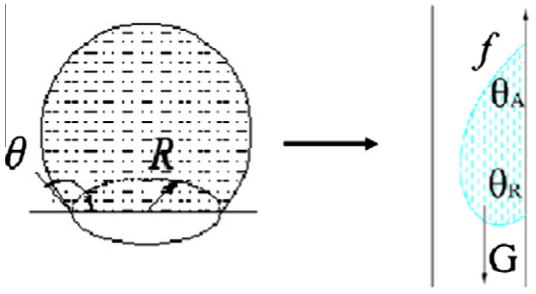

Fig. 1. Schematic of the water drop.