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Enhanced water removal performance of a slope turn in the serpentine flow channel for proton exchange membrane fuel cells

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ABSTRACT

Aim to effectively improve the removal and transport of liquid water in the flow channel in a proton exchange membrane fuel cell (PEMFC), we designed a slope turn in the serpentine flow channel and conducted numerical simulations using volume-of-fluid method to investigate the water behavior in it. To optimize the slope turn, the effects of the sectional area and slope angle of the slope turn and the wettability of channel wall on the transport and dynamics of water were investigated. Besides, cases with different sizes of single water droplet and the interactions between multiple droplets were also considered. For single droplet, the results suggest that with the designed slope turn, water droplet can be effectively removed from the surface of membrane electrode assembly (MEA) though the channel walls are hydrophobic. Without slope turn, the water droplet is transported downstream, always being attached on the MEA surface. The designed slope turn is also applicable for the case of multiple droplets to enhance water removal from the MEA surface.

1. Introduction

Proton exchange membrane fuel cell (PEMFC) is a powerful system which directly converts the chemical energy of fuel and oxidant into electricity [1–4]. Attributed to low emission and high efficiency, it is considered to be one of the most promising options for the low-carbon future [5–7]. However, there are still some insurmountable difficulties for its widespread commercial applications, such as water management, which seriously affects the cell output, cost and reliability [8–13]. In a PEMFC, water is produced in the cathode catalyst layer (CL), then transported through the gas diffusion layer (GDL) to the MEA surface, and finally drained out of the flow channel [14]. Once the produced water cannot be removed in time, it may accumulate in the GDL or flow field, which not only decreases the local reactant concentration, but also increases the pressure drop. In consequence, it would lead to parasitic power loss and poor cell performance [15–18].

The flow field in a cell is the last pathway for the transport of water, and its configuration has a great influence on the capability of water removal and transport. The common configurations include parallel, interdigitated and serpentine layouts, and their alternations or combinations [19–23]. In general, parallel flow field requires low pressure, but it suffers from severe flow maldistribution, which decreases the capability of water transport and leads to low cell performance [24]. Interdigitated flow field can force the reactant to flow through the GDL and blow out the entrapped liquid water, which gives rise to satisfied water removal capacity and high cell performance, but it requires extremely high pressure [25,26]. Serpentine flow field possesses better water transport capability and cell performance than parallel flow field, and its pressure drop is not so high as interdigitated flow field [27,28]. Therefore, the serpentine flow field has been more widely used and researchers have made great efforts to further improve its water removal and transport capability and cell performance [29,30]. Williams et al. [31] experimentally found that the serpentine flow field has convections under ribs, which helps blow out the entrapped liquid water in the GDL. According to this finding, Xu et al. [29] presented a convection-enhanced serpentine flow field, which could increase the pressure differences between adjacent flow channels and enhance cross-flow through the GDL. The new design reduces the amount of liquid water entrapped in the GDL and improves the cell performance and operating stability. In addition, Vazifeshenas et al. [32] presented a novel compound serpentine flow field to accelerate the flow rate in the exit region by reducing the sectional area of channels, which was found to be beneficial to the water transport.

Wettability is an important factor in the removal and transport of liquid water in the flow field. Jo and Kim [33] investigated the dynamics and transport of liquid water through a right angle and revealed that the hydrophobicity of the MEA surface and channel walls has an important effect on the transport process of liquid water. Mondal et al.

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[34] simulated the transport process of liquid water in the flow channel, and they discovered that liquid water transport is greatly affected by the channel surface wettability and air flow conditions. Tang et al. [35] investigated the removal and transport of liquid water with the neutron imaging technique, and they found that super-hydrophobic channel helps transport liquid water in the flow channel while super-hydrophilic channel helps remove liquid water from the MEA surface, both of which are beneficial to water management. Hou et al. [36] also carried out simulations to investigate the effect of wall wettability on the water removal, and they found that hydrophilic walls make it more difficult to transport liquid water in the channel due to strong adhesion, while it is converse for hydrophobic walls.

Since the accumulation of liquid water on the MEA surface may prevent the reactants from diffusing into the MEA, great efforts have been made on designing local structures of the flow channel by incorporating wall wettability to remove water from the MEA surface. Quan and Lai [37] reported that a sharp corner in flow channel could provide space for water to accumulate and climb up onto the hydrophilic channel walls, hence reduce the area covered by water on the MEA surface. Metz et al. [38] presented a micro-structured flow channel composed of a triangular micro-channel and a rectangular micro-channel, both with hydrophilic walls. With the designed flow channel, the water droplets can be detached from the MEA surface, then lifted into the rectangular micro-channel, and finally removed from the MEA surface thoroughly. Qin et al. [39,40] inserted hydrophilic needles or plates in the middle of straight channels and found that the modified flow channels can significantly remove water from the MEA surface. Utaka and Koresawaa [41] presented a gas separator with hydrophilic microgrooves to enhance liquid water removal, and they experimentally found that cell voltage fluctuation induced by liquid water was reduced and the stability of the cell voltage was improved. As can be seen from the above context, most of the flow channels are designed to be hydrophilic to enhance detachment of liquid water from the MEA surface. However, hydrophilic walls would decelerate the water transport in the channels because of its strong adhesion on the walls [36,42,43].

In this work, we presented a modified serpentine flow channel with a slope turn, utilizing the slope turn rather than the hydrophilicity of the channel walls to enhance water removal from the MEA surface. In order to evaluate the performance of the design, we carried out computational fluid dynamics (CFD) simulations with volume-of-fluid (VOF) method to explore the transport and dynamics of liquid water in the modified flow channel. To optimize the slope turn, the effects of the sectional area and slope angle of the slope turn and the wettability of channel wall on the transport and dynamics of liquid water were investigated. Besides, cases with different sizes of single droplet and the interactions between multiple droplets were also considered.

2. Model formulation

2.1. Computational domain and assumptions

The computational domain involves the conventional channel and modified channels shown in Fig. 1. Compared with the conventional channel, the modified channel has the same straight parts, which are 8.5 mm, 1 mm and 1 mm along *X*, *Y* and *Z* directions, respectively, and a different channel turn at which a slope replaces the semicircle outer wall. The structure of the slope is determined by slope angle (θ_{slope}), which is defined as the angle between the center line of the slope and the MEA surface.

Water is produced by electrochemical reaction in catalyst layer and its generation rate depends on local current density. According to previous work [44], the water flux can be given as

$$N = \frac{M(1 + 2\alpha)i}{2F} \tag{1}$$

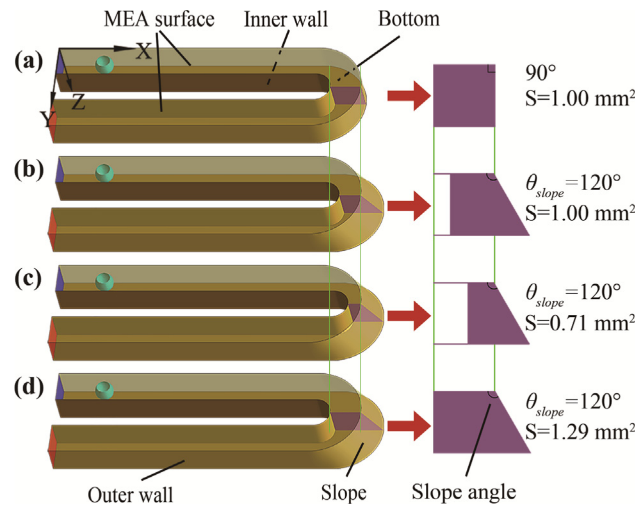

Fig. 1. Computational domain: (a) conventional channel, (b) modified channel with normal sectional area, (c) modified channel with small sectional area and (d) modified channel with large sectional area.

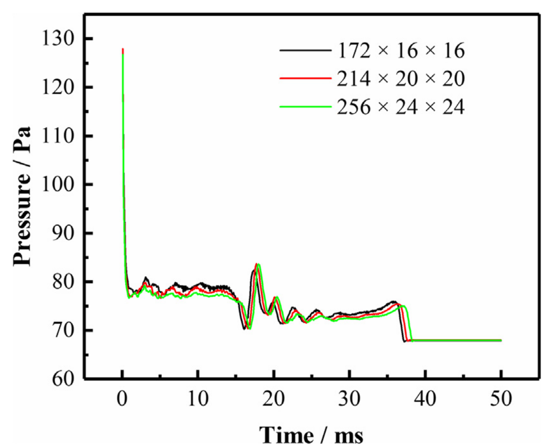

Fig. 2. Results of grid independency test for pressures in the conventional serpentine flow channel with three sets of grid numbers.

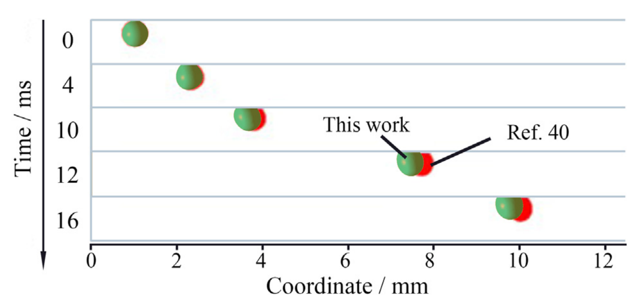

Fig. 3. Comparison of water transport in a straight channel between this work and reference.

where *M* is the molecular weight of water, α is the net water transport coefficient in the membrane, *i* is the fuel cell operating current density and *F* is the Faraday constant. In an operating PEMFC, water continuously enters the flow channel from the micro-channels on the interface between the MEA surface and the flow channel. In order to observe and analyze the transport of liquid water at the channel turn clearly and conveniently, we first considered the case of a single water droplet on the MEA surface in the flow channel.

The size of the droplet is influenced by current density, humidity conditions and gas velocities in an operating PEMFC. Yang et al. [45]