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Visualization of two-phase flow and temperature characteristics of an active liquid-feed direct methanol fuel cell with diverse flow fields

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HIGHLIGHTS

- Two-phase flow phenomena of a liquid-feed DMFC are visually investigated.
- The serpentine, parallel and porous flow fields are evaluated.
- Different impact factors are compared among three flow field patterns.
- The use of serpentine flow field yields a higher cell performance.
- Temperature characteristics in the serpentine channel are also discussed.

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ABSTRACT

Direct methanol fuel cell (DMFC) is a promising power source for portable applications. This study aims to reveal the two-phase flow characteristics of an active liquid-feed DMFC by using the visualization method. Different flow fields based on the serpentine, parallel and porous patterns and their effects on reactant and product managements are experimentally investigated. Results show that the performance of serpentine flow field is closely influenced by the change of methanol feed rate but the parallel pattern shows less sensitivity. The use of serpentine flow field enables the fuel cell to be operated with a higher methanol concentration. A higher methanol feed rate promotes removal of the produced gas bubbles. The oxygen feed rate has a negligible effect on the fuel cell with a cathode serpentine flow field but produces a more obvious performance difference in the case of parallel pattern. The visualization tests indicate that the use of a higher oxygen flow rate is helpful in water removal. The temperature characteristics of the anode serpentine channel are evaluated and how the temperature behaviors relate to different operating conditions are accordingly discussed.

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1. Introduction

As one of the next-generation power sources for portable applications, the direct methanol fuel cell (DMFC) is regarded as a promising candidate due to its alluring advantages such as high energy density, low emission, compact structure, easy refueling and fuel security. Besides, unlike the volatile hydrogen gas, direct use of the liquid methanol enables the DMFC to be operated without complex auxiliary devices, e.g. reformer, heat exchanger and humidifier, so as to reduce the parasitic power loss to a great degree [1–6]. When the cell is subject to passive reactant delivery based on a reservoir-included anode and an air-breathing cathode, its energy density and system efficiency are both supposed to be even higher than the active system, because the power-consuming actuators like pumps and blowers are no more required [6–8]. Therefore, many researchers are devoted to the study on passive DMFCs in recent years [9–16]. However, a passive DMFC mostly suffers from a great loss in electrochemical performance due to mass transfer limitation and catalytic inactivity [13]. From the view of practical use, the primary goal is to get a higher power output. Thus, active supply of the reactants is still preferred for the sake of a higher power density. In this case, the top priority is to handle the technical issues related to optimization of the fuel cell structure, materials and operation in an active-feeding mode. All these issues greatly influence the performance, efficiency, cost and endurance of a fuel cell for real applications.

In the field of DMFCs, the problems related to the flow distributor/bipolar plate have attracted broad attentions. Like the case for a hydrogen fuel cell, the flow distributor functions as a

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critical component affecting the transport and distribution of reactants and products [17]. In particular, as a mass-transfer medium, the flow field patterned with different channels plays very important roles in regulating the two-phase flow [18,19]. As is well known, carbon dioxide (CO_2) is produced in the form of bubbles at the anode and may accumulate increasingly in the channels. Under this condition, if the bubbles cannot be exhausted smoothly, methanol supply will be hindered and thereby the anode reaction layer will take more risk of fuel starvation. Likewise, the cathode electrode possibly encounters water flooding in the presence of both permeated and produced water. This is also likely to induce channel blockage so as to impede oxygen intake. What is worse, a troubling issue is that the popular polymer membrane based on Nafion-series fails to resist methanol crossover (MCO) from the anode to the cathode. The permeated methanol at the cathode may directly react with the oxygen, producing a mixed potential that greatly drags down the cell voltage [20,21]. From the above statement, it can be inferred that an optimal design of the flow field is of great importance to the management of the fuel, gas and water in a DMFC [22].

The open literatures have reported various patterns of flow field, namely the serpentine, parallel, grid, interdigitated, spiral, fractal and even combination of these types [1,23–29]. In particular, for passive DMFCs, perforated flow fields are mostly used to provide transport passages for both reactants and products [30]. Some researchers tried to use a mesh or porous sheet instead of the graved channels in order to eliminate the effects of rib areas [31–34]. Among these flow bed patterns, the serpentine one is usually adopted since it has a larger path length for fluid flow and promotes a higher pressure drop to enhance mass transfer. Moreover, this type can be easily fabricated by use of many mature technologies. A few studies focused on the effects of geometric parameters such as channel width, depth and interval space. Hwang et al. [35] reported on the impact of cathode channel depth on the performance of a DMFC. Results indicated that the decrease of channel depth benefited enhancing mass transport and linearly increased the cell performance. Contrarily, Vijayakumar et al. [36] discovered that it was counteractive to further reduce the channel depth owing to the increase of MCO caused by the effect of convective mass transfer. Kianimanesh et al. [25] concluded that a smaller width of the single serpentine channel with the same effective area generally yielded a higher performance. In most cases, researchers like to use the same layout for the anode and cathode. In this regard, many studies have validated the advantages of using serpentine flow fields on both sides of the fuel cell [35–39]. There have been plenty of evidences showing that the serpentine pattern facilitates a more uniform distribution of the reactants. However, some people paid more attention to the influence of diverse flow field combinations on both sides of the fuel cell. Jung et al. [24,40] claimed that the anode parallel channel coupled with a cathode serpentine channel presented the best cell performance. They attributed this result to the fact that the serpentine design exhibited higher mass-transfer ability in excluding water on the cathode side.

In order to improve the performance of serpentine flow fields, researchers have proposed a variety of optimization strategies. For example, Li et al. [41] introduced a conceptual design of non-equipotent serpentine flow field to mitigate CO_2 bubble clogging in a μ-DMFC. The channel width from the outlet to the inlet was gradually reduced leading to a more uniform bubble distribution and faster gas removal. Similarly, Zhang et al. [42] designed a tapered flow field for a μ-DMFC to enhance the pressure difference between two adjacent channels so as to gain a higher mass transport efficiency and with it a better performance. They [43] also investigated the corner effect on micro-scale flow and proved that the circular corner promoted faster emission of CO_2 bubbles than the orthogonal design. Xu and Zhao [44] made a new flow field with enhanced under-rib convection by forming a larger pressure difference between adjacent channels. This idea was proven helpful to the increase of mass transport rates of both reactants and products, which minimized water flooding over the whole electrode area. Hutzenlaub et al. [45] negated bubble pinning in the flow channel and realized bubble travelling at the mean fuel velocity by enhancing the hydrophilicity of the channel walls. By changing the wettability of flow filed, Yeh et al. [46] demonstrated that the hydrophobic channels are superior to hydrophilic channels since it helps not only remove the CO_2 gas but also improve electric output of a DMFC under various operating conditions. Interestingly, Lundin and McCready [47] presented a model to predict the effectiveness of limiting the gas bubble formation by using chemically enhanced solubility at the anode, providing a potential method for bubble reduction in a DMFC.

Some of these studies resorted to visualization methods to look deep into the two-phase phenomena in the anode and cathode compartments. With the aid of direct observation by digital cameras, more details about the two-phase flow characteristics can be amplified, which will guide us to optimize the structure and operation of the fuel cell. Argyropoulos et al. [48,49] focused on gas evolution and its influence mechanisms by using visualization methods in their early studies. Lu and Wang [50] presented a small-scale transparent DMFC to visualize the anode bubble dynamics and also cathode flooding. Liao et al. [51] visually inspected the dynamic behaviors of the CO_2 bubbles in the anode channel and also analyzed the effects of different operating parameters such as methanol feed rate, feed temperature and feed concentration. Yuan et al. [52] conducted a visual study on the CO_2 transmission in a μ-DMFC through modeling and experimental approaches, concluding that the operating current, flow rate and temperature had significant influences on the quantity and shape of CO_2 bubbles. Zhao and coworkers [53–55] systematically evaluated the gas bubble behaviors, capillary blocking and anode flow channel parameters of the DMFC based on a visual design. Bewer et al. [56] made a visible dummy cell to simulate the two-phase flow of a real DMFC. Their core idea was to use aqueous H_2O_2 solution to generate gas bubbles via decomposition reaction in the presence of a catalyst. Following this method, Liang et al. [57] developed a hybrid flow field with superhydrophobic gas channels and hydrophilic fuel channels to speed up the discharge process of produced gas bubbles. To magnify the on-site images, some other people measured the mass flow by use of micro particle image velocimetry (μPIV) [58,59]. The above contributions primarily deal with the anode visualization but barely discuss on the cathode situation. In this regard, Wang et al. [60] visually validated the feasibility of creating a superhydrophilic coating on the surface of an aluminum-based cathode current collector to solve the problem of cathode water flooding for a μ-DMFC. Their results showed that the liquid water could spread quickly on the surface of the porous coated layer so as to evade accumulation of water droplet along the channels of current collector.

The above short review indicates that the flow field design relates closely to the mass transfer efficiency and performance of a DMFC. For two-phase flow investigation on both sides of the fuel cell, it is quite useful to have a better insight into the mass transport and evolvement in the flow channels by using visualization methods. As summarized in Table 1, we can get a general view on the current literatures which concentrate more on the anode dynamics but less on the cathode, especially the two-phase flow and temperature characteristics. Moreover, the comparison between different flow fields still deserves more in-depth investigation because there are complex factors impacting on the mass transport or even interacting with each other. In this context, the objective of this study is to visually inspect the two-phase flow

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