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Lightweight current collector based on printed-circuit-board technology and its structural effects on the passive air-breathing direct methanol fuel cell

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To realize lightweight design of the fuel cell system is a critical issue before it is put into practical use. The printed-circuit-board (PCB) technology can be potentially used for production of current collectors or flow distributors. This study develops prototypes of a single passive air-breathing direct methanol fuel cell (DMFC) and also an 8-cell mono-polar DMFC stack based on PCB current collectors. The effects of diverse structural and operational factors on the cell performance are explored. Results show that the methanol concentration of 6 M promotes a higher cell performance with a peak power density of 18.3 mW cm^{-2}. The combination of current collectors using a relatively higher anode open ratio and inversely a lower cathode open ratio helps enhance the cell performance. Dynamic tests are also conducted to reveal transient behaviors and its dependence on the operating conditions. To validate the real working status of the DMFC stack, it is coupled with an LED lightening system. The performance of this hybrid system is also reported in this study.

1. Introduction

To use liquid fuel instead of hydrogen gas for polymer electrolyte membrane fuel cells opens out a bright prospect because it is more likely to be used for portable electronic products [1]. In this field, the direct methanol fuel cell (DMFC) can be potentially used as a candidate power source due to its high energy density, safe fuel storage, convenient refueling, simplified configuration and low emission [2,3]. However, before the DMFC is put into practical use, we must tackle many challenging issues including the catalytic inactivity, methanol crossover (MCO) in the Nafion-based membrane and mass and heat transfer limitation caused by low-temperature operation. In particular, the existence of MCO inevitably leads to severe voltage losses, fuel waste and even catalyst poisoning, thereby reducing power output, fuel efficiency and operating time for a run of discharging [4,5]. When the DMFC works in a passive manner with an open anode depending on spontaneous methanol permeation and also an air-breathing cathode fed with the surrounding air/oxygen, the above deficiencies may be more prominent since it abandons the parasitic devices and operates in a near-ambient environment [6,7]. In view of the demand for real commercialization, further considerations should cover the issues toward light-weight design, structural optimization, cost efficiency, environmental adaptation and easy-to-use properties.

To address the aforementioned problems or at least alleviate their influences, plenty of attempts have been made to optimize design and fabrication of the key components such as the membrane electrode assembly (MEA) and current collector. As for a passive air-breathing DMFC, the current collector not only helps collect the generated electricity and support the MEA, but also serves as a reactant distributor to provide fluid flow passages. Evidently, a competent current collector must own higher conductivity and lower contact resistance when it is laminated together with the MEA. Moreover, an optimized opening pattern with featured geometric parameters is necessary to assist regulating the mass transfer process.

In the fuel cell communities, many contributions were devoted to potential materials to make current collectors or flow field plates. Most of the early studies used graphite to create such components

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since it is capable of providing good electrical and thermal conductivity [8,9]. However, such carbon-based composite materials mostly lead to a lower yield rate and a higher production cost since it has poor machinability, lower mechanical strength and brittleness. To overcome these handicaps, some people transferred their attentions to the use of metallic materials including metals and alloys because they are intrinsically conductive and also likely to be made into thin sheets so as to decrease the weight and cost of the current collectors [10–12]. The main disadvantage of using a metallic current collector lies in the fact that it is likely to be corroded in the acidic environment of a Nafion-based fuel cell and thereby triggers severe performance degradation [13,14]. To this end, various coating and alloying methods were implemented to enhance the corrosion resistance of the metallic current collector. A typical treatment is to use the gold-plating technique to coat a protective layer on the metallic substrates [15–17]. In addition, the advances of micro-electro-mechanical-system (MEMS) technology enable using silicon-based materials to make current collectors for micro-DMFCs [18].

Despite the importance of material selection and protective treatment, optimization of the flow field structure has also drawn broad attentions. In the case of active DMFCs, the flow field is mostly formed by fabricating channels with different shapes like parallel, serpentine, interdigitated and spiral patterns. The flow state and distribution characteristics of the fluid reactants are closely related to the structural parameters of the channels at both the anode and cathode [19–21]. Some studies [22–25] attempted to modify the flow channels by setting spoke-like structures, micro-blocks, shutters and pin-fins to optimize the flow distribution. Interestingly, non-uniform flow field design can also benefit the mass transfer behavior [26]. As for a passive DMFC, its flow field commonly changes into an open form to provide passages for reactant feeding and product removal. In this case, the opening patterns and open ratios of the flow distributor (i.e. current collector) have great effects on the passive DMFC [18,27–32]. Besides, there is also evidence indicating that the interactions between the current collector openings and the structural parameters of other components like the diffusion layer and membrane must be also considered [31]. In order to lessen mass diffusivity of the flow field medium, some researchers tried to use porous materials based on metal foams, meshes and sinters to replace the traditional grooved or perforated flow fields [33].

From the perspective of stack architecture, passive DMFCs with an air-breathing cathode are mostly assembled in the form of planar mono-polar stack [34,35] and bi-cell twin stack [36]. Besides, some works highlighted the feasibility of using printed-circuit-board (PCB) techniques to construct DMFC stacks with multi-cells internally connected in series. The PCB with a certain opening pattern serves as a current collector and a reactant flow distributor simultaneously, which also helps carry electronic elements and output sockets. This embodiment facilitates a more compact, lightweight structure of the passive air-breathing DMFC. It is also imperative to conduct surface coating on the exposed areas of the PCB, because the released fluorion from the Nafion membrane and corrosion product (e.g. Cu^{2+}) possibly result in performance deterioration of the fuel cell [17]. The PCB technology had been applied to the hydrogen-based fuel cell prior to the DMFC [37]. Lim et al. [38] reported the earliest findings on an air-breathing multi-DMFC with micro channels machined on a PCB substrate by means of a photolithography process, evaluating the effects of different channel patterns. Kuan et al. [39–41] fabricated a planar PCB-DMFC module and looked into its structural and operational features. They also tried to use a composite epoxy plate as the substrate of current collectors and coated two metal films to create a corrosion-resistant layer. Baglio et al. [42,43] demonstrated a PCB-based DMFC mini-stack with a planar mono-polar configuration.

It is thus far clear that the current collector of a DMFC plays important roles in the mass transfer mechanisms, so it must be reasonably optimized. In this case, how to address the issues with regard to design, manufacturing and functional characteristics of the current collectors is of great significance to the development of this type of fuel cell. In this context, the present work aims to provide prototypes of a PCB-based passive air-breathing DMFC and also an 8-cell mono-polar stack. The focus of this study will be put primarily on the effects of methanol concentration, current collector opening pattern and also dynamic operation. Therefore, this work illuminates how to realize lightweight fuel cell design and effective management of the mass transfer processes.

2. Experimental

2.1. Structural design of passive air-breathing DMFC

In this study, a single DMFC with an effective area of 9 cm^2 and an annular mono-polar 8-cell stack were prepared for performance evaluation. They were both based on PCB structures. The anode of the single cell (see Fig. 1) used a transparent fuel chamber with a built-in reservoir for methanol storage while the cathode operated in an air-breathing mode. Two through holes were machined in the top wall of the chamber for both fueling and gas ventilation. The anode and cathode current collectors were made from 1 mm-thick epoxy laminates (FR4) plates coated with a gold layer (0.2 μm) to enhance electrical conductivity. Four patterns of the current collectors with different openings and open ratios are illustrated in Fig. 2. The geometric parameters of each pattern are specified in Table 1. In order to avoid severe MCO and promote oxygen intake, the circular-hole-array (CHA) and parallel-fence (PF) patterns were respectively used at the anode and cathode. This design has been proven to be helpful to enhance MCO resistance at the anode and promote oxygen intake at the cathode, since the CHA pattern yields a lower open ratio whereas the PF pattern mostly provides a larger open area. For stack design, the substrate of the anode PCB with a thickness of about 1.1 mm was also made from the FR4-based composite material whose surface was covered with a thin layer of black ink (see Fig. 3). An electric circuit was embedded inside the PCB so as to interconnect the unit cells in series and also carry the electronic elements. For the cathode, a copper-clad aluminum substrate with a thickness of 1.6 mm was used as the PCB current collector on which a layer of white ink was attached. The exposed surface of MEA and welding pads were also gold-coated. Likewise, the anode and cathode PCBs of the stack also used CHA and PF patterns respectively with an open ratio of 22 and 43%. The holes of the PCBs were made by using a perforating machine. The effective

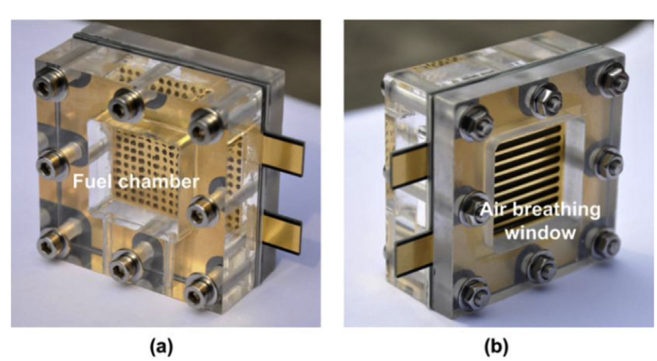

Fig. 1. Photos of the passive air-breathing DMFC: (a) anode; (b) cathode.