A Self-vortical Micromixer and its Application on Micro-DMFC

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ABSTRACT

Microfluidic micromixer is a very important component of microfluidic biochip for the fluidic mixing procedure of small volume biological sample and reaction reagents. In addition, microfluidic micromixer is possible to be used in a micro-DMFC (direct methanol fuel cell).

In a micro-DMFC, methanol fuel and water management is a critical issue to enhance the fuel cell performance and keep fuel cell operation for an extended period of time. In order to maintain the specific concentration of methanol fuel, some of micro-DMFC designs contain external methanol fuel and water mixing tank for premixing, and then feeding into micro-DMFC. However, methanol fuel and water mixing tank is difficult to be miniaturized and integrated into a micro-DMFC. In this paper, we demonstrate the micro-DMFC, with an internal methanol fuel mixing function, is able to mix methanol fuel and water by the self-vortical micromixer inside itself.

Keywords: micromixer, fuel cell, micro-DMFC

1 INTRODUCTION

Microfluidic micromixer is an important component used in lots of the micro-chip microfluidic systems for biochemistry analysis, drug delivery and sequencing or synthesis of nucleic acids [1]. For example, microfluidic biochip use a micromixer in the fluidic mixing procedure of small volume biological sample and reaction reagents [2]. In addition to micro-chip microfluidic systems, microfluidic micromixer is possible to be used in a micro-DMFC.

Fuel cell is an electrochemical power generator that converts the chemical energy of a chemical reaction to electricity. The electrochemical reaction equations of a DMFC are listed as below:

Anode reaction: $CH_3OH + H_2O \dashrightarrow CO_2 + 6\,H^+ + 6e^-$
Cathode reaction: $6\,H^+ + 3/2\,O_2 + 6\,e^- \dashrightarrow 3\,H_2O$
Overall reaction: $CH_3OH + 3/2\,O_2 \dashrightarrow CO_2 + 2\,H_2O$

Fuel cell consists of an electrolyte membrane (proton exchange membrane, PEM), anode components comprising of anode catalyst layer, gasket, anode plate and flow field plate, as well as cathode components consisting of cathode catalyst layer, gasket and cathode plate. PEM supports hydrogen proton to migrate from anode components to cathode components. Electron generates from anode reaction and migrates from anode plate to cathode plate. Electricity is able to generate by connecting anode plate and cathode plate.

A DMFC has higher power density and relatively high energy-conversion efficiency than a lithium ion battery [3]. Therefore, a DMFC is able to miniaturized to become a micro-DMFC as a favorable candidate for the increasing energy demand of portable electronics, such as cellular phones, laptop computers and PDAs, etc. Nevertheless, in a micro-DMFC, methanol fuel and water management is more difficult than a DMFC.

The methanol fuel with specific concentration as a reductant is fed to the anode components for oxidation reaction on the anode of a fuel cell. The oxygen from air as an oxidant is supplied to the cathode components for reduction reaction on the cathode of a fuel cell. Therefore, the power performance of a micro-DMFC is very sensitive with both the concentration of providing methanol fuel to anode components and the flux of providing oxygen to cathode components.

In order to maintain the specific concentration of methanol fuel, some micro-DMFC designs have external methanol fuel and water mixing tank for premixing, and then feeding into a micro-DMFC. However, methanol fuel and water mixing tank is difficult to be miniaturized. For miniaturization of micro-DMFC, in this study, we propose an internal mixing tank of micro-DMFC and develop the new passive micromixer, the self-vortical micromixer, and integrated this micromixer into a micro-DMFC.

2 EXPERIMENTAL

2.1 Micromixer and Fuel Cell Design

Micromixers could be categorized into passive micromixers and active micromixers. Active micromixers mix microfluids by either actuating movable parts or using external forces, such as pressure disturbance, electrical field, magnetic and acoustic vibration, to achieve mixing effect. Passive micromixers use complicated shapes and structures along microchannel via complicated micromachining processes, and usually require the mixing channels with considerable length and novel design to enhance geometric stirring [4-5].

Figure 1(A) and (B) show the schematic diagram of microfluidic mixing principle of the self-vortical micromixer developed in this study. In the self-vortical micromixer, two fluids separately inject into two inlet reservoir and separately flow into two inlet channel simultaneously, and then the two fluids are able to generate the self-vortical mixing phenomenon in the circular mixing chamber. The mixed fluid mixture of two fluids is able to flow into the mixing channel and achieve complete mixing.

The self-vortical micromixer is made by assembling the upper flow field plate and lower flow field plate. Figure 1(C) presents the upper flow field plate containing two inlet channels both with a width of 500μm and a depth of 150μm, one circular mixing chamber with a diameter of 2000μm and a depth of 150μm, as well as two inlet reservoirs both with a diameter of 5000μm and a depth of 20mm. The lower flow field plate contains one serpentine micro-channel with a width of 500μm and a depth of 150μm, and one outlet reservoir with a diameter of 5000μm and a depth of 20mm.

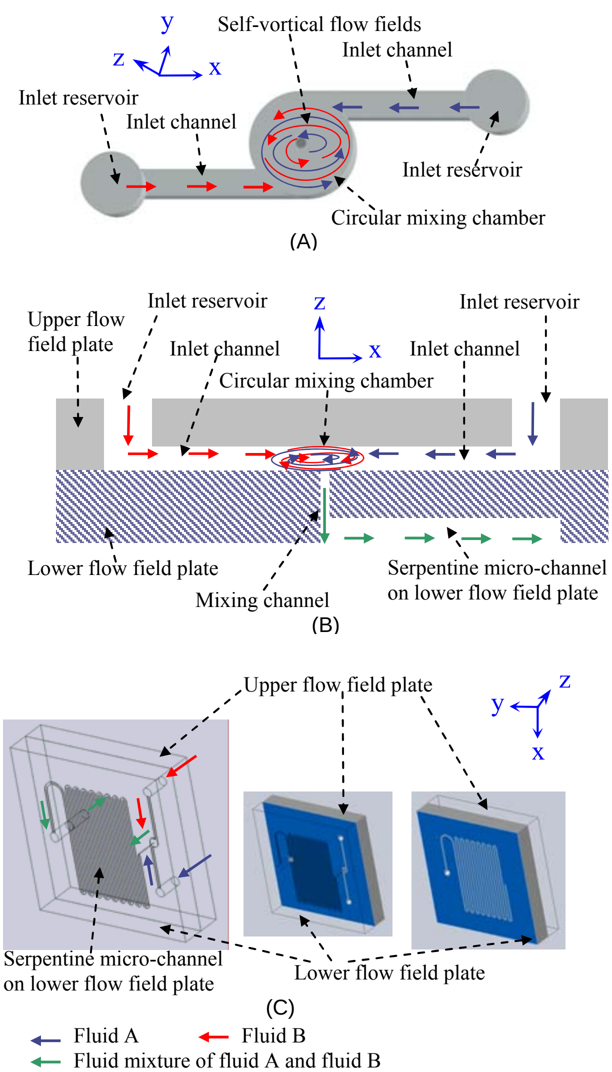

Figure 1: The microfluidic mixing principle and design of the self-vortical micromixer. (A) Top-view of the microfluidic mixing principle of the self-vortical micromixer. (B) Cross-section view of the microfluidic mixing principle of the self-vortical micromixer. (C) The designed self-vortical micromixer integrated into the serpentine micro-channel on lower flow field plate of the micro-DMFC.

Figure 2 shows the assembly picture of the micro-DMFC integrated with the self-vortical micromixer developed in this study. The self-vortical micromixer consists of upper flow field plate and lower flow field plate.

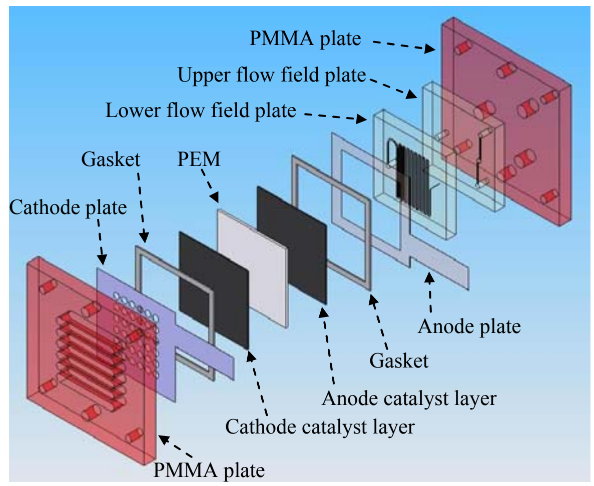

Figure 2: The assembly picture of the micro-DMFC.

2.2 Micromixer CFD Simulation

The computational fluid dynamics (CFD) simulation results can predict the flow velocity profiles and the flow streamlines of microfluidic system [6]. Figure 3 illustrates the CFD simulation result of the micromixer by utilizing the commercial CFD package software program (CFD-ACE+, CFD Research Corporation, CA, USA).

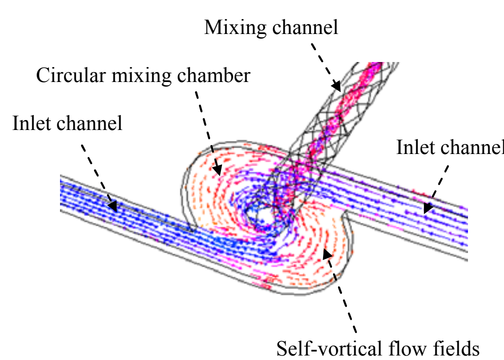

Figure 3: The CFD-ACE+ simulation results of the flow velocity profiles and the flow streamlines in the circular mixing chamber of the self-vortical micromixer. The directions of the vectors represent the directions of flow velocities.

2.3 Micromixer and Fuel Cell Fabrication

The self-vortical micromixer, developed in this study, consists of the upper flow field plate and the lower flow field plate. We used the polydimethylsiloxane (PDMS) material to fabricate both upper flow field plate and lower flow field plate by the PDMS replica molding method [6]. The PDMS made upper flow field plate has the micro feature patterns and involves two inlet channels, one circular mixing chamber and two inlet reservoirs; on the other hand, the PDMS made lower flow field plate has the micro feature patterns and includes one serpentine micro-channel and one outlet reservoir. These micro feature patterns mentioned above on the replication mold were fabricated by thick-film photoresist photolithography process, using a chrome photo mask. Next, PDMS pre-polymer was poured on the replication mold, hardened after baking process, and then we peeled the hardened PDMS from the replication mold to separately made the PDMS made upper flow field plate and the PDMS made lower flow field plate. Finally, we used PDMS oxygen plasma treatment for bonding of the PDMS made upper flow field plate and the PDMS made lower flow field plate.

As shown in Figure 2, we developed the micro-DMFC which was assembled by the following parts: PMMA plate (anode side), upper flow field plate, lower flow field plate, anode plate, gasket (anode side), anode catalyst layer, PEM, cathode catalyst layer, gasket (cathode side), cathode plate and PMMA plate (cathode), Figure 4 shows the photograph of the assembled micro-DMFC.

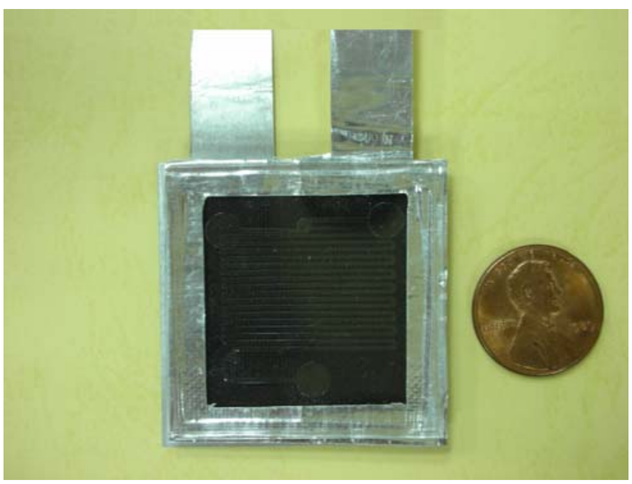

Figure 4: The photograph of the micro-DMFC.

2.4 Micromixer Testing

As shown in Figure 5, we demonstrate the fluidic mixing performance of the self-vortical micromixer. At the same time, a blue color dye fluid and a yellow color dye fluid were separately injected into two inlet channels by syringe pump and then flowed into the circular mixing chamber to form swirly flow fields and further generated the self-vortical flow fields. The blue color dye fluid and yellow color dye fluid were mixed in the downstream of the mixing channel by the self-vortical flow fields.

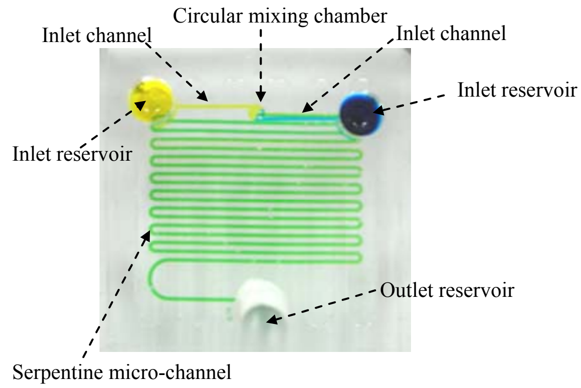

Figure 5: The testing result of the self-vortical micromixer.

As shown in Figure 6, we characterized the mixing efficiency for the self-vortical micromixer by using the definition of the mixing index [7].

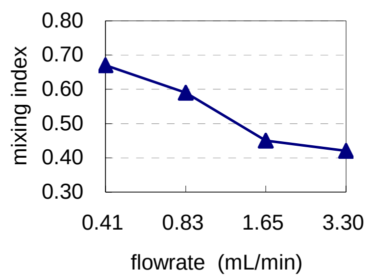

Figure 6: The testing results of mixing index for two different color dye fluids mixed in the circular mixing chamber of the self-vortical micromixer. The lower mixing index means the better mixing efficiency.

2.5 Fuel Cell Testing

Methanol solution with a concentration of 9.0% was prepared to test the performance of the micro-DMFC. Two pumps with same flow rates of 2.4mL/min were used to separately deliver the 9.0% methanol solution and DI water into one of the two inlet reservoirs of the self-vortical micromixer inside the micro-DMFC. After fluidic mixing by the self-vortical micromixer, the mixed fluid mixture of 9.0% methanol solution and DI water had a concentration of 4.5%. The mixed fluid mixture was transported to the serpentine micro-channel (area was 2.45 cm^2) on the flow field plate of the micro-DMFC and flowed into anode components of the micro-DMFC. During the specific concentration of methanol fuel feeding, the cathode components of the micro-DMFC were exposed to ambient air for oxygen supplied by the air natural convection.

An fuel cell load test system was used to measure polarization curve at the polarization condition: scan voltage was 600 mV to 0 mV, voltage decrease step was 10 mV, and load interval time was 1 minute.

3 RESULTS AND DISCUSSION

The micro-DMFC shows an open circuit voltage (OCV) of 700mV. Figure 7 explains the polarization curves of current and voltage characteristic from the polarization test of single cell of micro-DMFC.

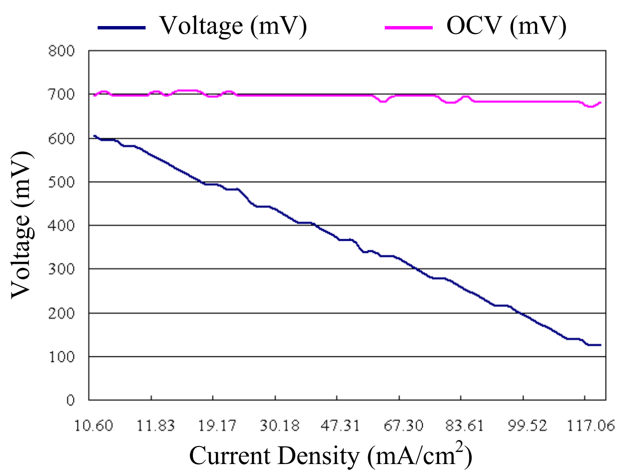

Figure 7: The current and voltage characteristic from the polarization test of a single cell of the micro-DMFC.

The power performance testing results reveal that the micro-DMFC had a maximum power density of 21.27 mW/cm^2. Figure 8 presents the power density curve of power performance of single cell of micro-DMFC.

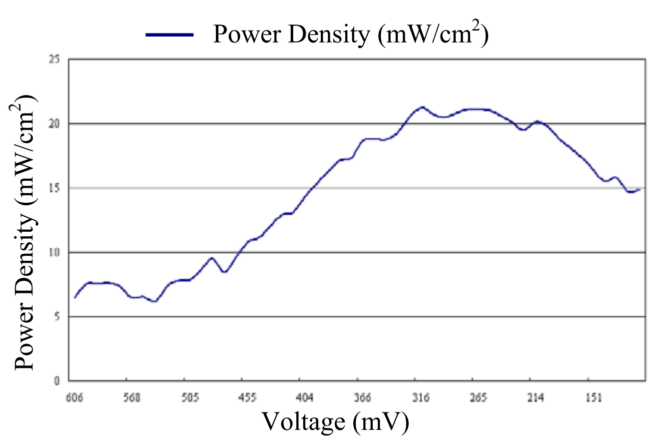

Figure 8: The power performance of single cell of the micro-DMFC.

4 CONCLUSION

In this paper, we demonstrate design and testing results of the self-vortical micromixer integrated with the micro-DMFC. It shows the self-vortical micromixer is able to be operated in a micro-DMFC system.

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