



## Effect of the cathode open ratios on the water management of a passive vapor-feed direct methanol fuel cell fed with neat methanol

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### ABSTRACT

A novel approach has been proposed to improve the water management of a passive direct methanol fuel cell (DMFC) fed with neat methanol without increasing its volume or weight. By adopting perforated covers with different open ratios at the cathode, the water management has been significantly improved in a DMFC fed with neat methanol. An optimized cathode open ratio could ensure both the sufficient supply of oxygen and low water loss. While changing the open ratio of anode vaporizer can adjust the methanol crossover rate in a DMFC. Furthermore, the gas mixing layer, added between the anode vaporizer and the anode current collector to increase the mass transfer resistance, can improve the cell performance, decrease the methanol crossover, and increase the fuel efficiency. For the case of a DMFC fed with neat methanol, an anode vaporizer with the open ratio of 12% and a cathode open ratio of 20% produced the highest peak power density, 22.7 mW cm<sup>-2</sup>, and high fuel efficiency, 70.1%, at room temperature of 25 ± 1 °C and ambient humidity of 25–50%.

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### 1. Introduction

The continuing explosion of portable devices such as MP3 players, smart phones, laptop computers, and GPS systems has placed tremendous pressure on power supply systems. However, the requirement of high power output, long operational time, small size, and light weight on the power supply systems cannot be fully met by the rechargeable lithium and nickel based battery systems which are presently used [1]. Due to the high theoretical energy density of methanol, the high power density of the direct methanol fuel cell (DMFC) makes it better suited for power-hungry, portable devices. Although it is a promising innovative power source, DMFC design is still in the prototype stage and the wide commercialization of DMFCs is hindered by several technical challenges, including methanol crossover, low catalytic activity, inadequate water management system, durability, and cost [2–5]. To reduce the performance degradation caused by methanol crossover, dilute methanol solutions (0.5–3 M) are usually fed to DMFCs so that the rate of methanol crossover can be reduced. However, operating the DMFC with low methanol concentration significantly decreases the energy density of the DMFC system. To ensure that DMFCs are compact enough for portable devices, produce adequate power, and are lightweight,

concentrated methanol solutions, or even neat methanol, should be supplied as the fuel.

Different approaches including improving the electrolyte membranes [6–8], improving the fuel-feed system [9–15], and altering the cell structure [16–21] have been proposed to achieve stable cell performance with high concentration methanol. Among these approaches, a change in the cell structures to improve the water management and decrease the methanol crossover is easy to implement and has attracted more attention.

The water management is extremely important in DMFCs fed with high concentration methanol [19,22], and the water management is highly related to the cathode structure of a passively DMFC. In DMFCs fed with high concentration methanol, the water flooding at the cathode side of the fuel cell is not significant and the passive supply of oxygen from the atmosphere is enough for the cathode reaction [22–24]. As a result, adding an extra hydrophobic porous material at the cathode as the water management layer or air filter layer can decrease the water loss and improve the water management in a DMFC fed with neat methanol without inhibiting the cell performance.

Xu et al. [21] studied the effects of the water management layer in a vapor-feed DMFC supplied with high concentration methanol. The results showed that by adding a water management layer, made from two 50 wt% polytetrafluoroethylene (PTFE) treated carbon clothes with the thickness of 480 μm, in the fuel cell using neat methanol, the peak power density was improved from 20 mW cm<sup>-2</sup> to 34 mW cm<sup>-2</sup>, and the fuel efficiency was increased from 44% to 62%. Masdar et al. [25] studied the effect of a hydrophobic air fil-

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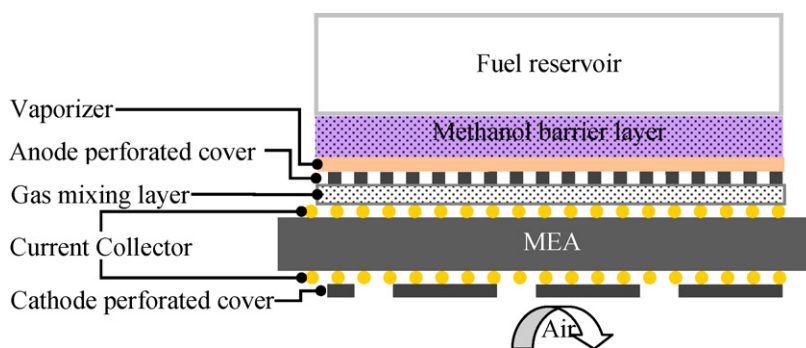


Fig. 1. Schematic diagram of a passive vapor-feed direct methanol fuel cell fed by neat methanol.

ter, made from 50 wt% PTFE treated carbon paper or compressed sheets of un-woven fabric with carbon black and PTFE, at the cathode on the water transport of a vapor-feed DMFC with 16 M to neat methanol. The air filter with a higher hydrophobicity and higher flow resistance was found to increase the water back flow, and consequently the current density.

However, the volume and the weight of the fuel cell are increased as a result of using thick water management layers or air filter layers. Another approach to decrease the water loss rate from the cathode is to decrease the open ratio of the cathode frame. A simple analysis has been conducted in the Appendix A to compare the effects of the thickness and the open ratio of the porous material on its mass transfer resistance. The mass transfer resistance of the porous material could be remarkably increased by significantly increasing its thickness or simply decreasing its open ratio. However, the effects of the cathode open ratio on the water management and the performance of a DMFC fed with high concentration methanol have not been reported. In this work, a vapor-feed passive DMFC fed with neat methanol will be developed without water management layers and air filter layers. Perforated plates with various open ratios will be used at the cathode of the DMFC to decrease the water loss, and the effect of open ratio on the water management and cell performance will be studied.

Methanol crossover is another key issue in DMFCs studies. Various materials have been used as the methanol barrier layer between the fuel reservoir and the membrane electrode assemble (MEA) to decrease the methanol crossover in DMFCs fed with high concentration methanol. The methanol barrier layer is typically hydrophobic porous materials with different permeability, which is determined by its physical properties such as porosity, tortuosity, and pore size distribution. Porous materials such as porous carbon plate [17], fired alumina layer [18], and porous PTFE plate [20] have been used as the methanol barrier layers. However, in DMFCs using neat methanol as fuel, the methanol crossover is so high that a very thick methanol barrier layer is required to decrease the methanol crossover rate to an acceptable level. Besides adding a methanol barrier layer, other approaches such as decreasing the open ratio of the vaporizer [19,21] and adding a gas mixing layer [17,26] between the fuel reservoir and the MEA in vapor-feed DMFCs have been adopted to further decrease the methanol crossover. The methanol concentration distribution throughout the MEA by using a vaporizer with small open ratio depends on the size, shape, and distribution of the open area of the vaporizer, it will not be as uniform as that using a methanol barrier layer. The methanol concentration distribution will be more uniform by adopting a gas mixing layer between the vaporizer and the MEA, which will further decrease the methanol crossover. In this work, besides using a thin methanol barrier layer, an anode gas mixing layer is added and the open ratio of the vaporizer was decreased in the vapor-feed DMFC fed with neat methanol to decrease the methanol crossover.

The combined effect of the vaporizer open ratio and the gas mixing layer on the cell performance will be studied.

## 2. Experiment

### 2.1. Fuel cell assembly

The structure of the passive DMFC fed with neat methanol is shown in Fig. 1. The methanol barrier layer was made from a hydrophobic PTFE membrane from Small Parts Inc. with a thickness of 3 mm, an average pore size of 30  $\mu\text{m}$ , and a porosity of 0.5. The vaporizer was made from a Nafion<sup>®</sup> 117 membrane with a thickness of 175  $\mu\text{m}$ . The anode and cathode perforated covers were made from PTFE films with 250  $\mu\text{m}$  thickness, and their open ratios varied from 5% to 38% by poking holes, as shown in Fig. 2. The anode perforated cover was attached to the vaporizer and change its open ratio. The gas mixing layer was created by adding a rubber gasket in the shape of a rectangle and hollow on the inside with a thickness of 2 mm placed between the anode perforated cover and the current collector to mix the methanol vapor with the generated carbon dioxide gas and the water vapor flows from the cathode. The current collectors were made from platinum coated niobium expanded metal mesh.

The MEA consisted of a catalyst coated membrane (CCM) from BCS Fuel Cells, Inc. sandwiched between two home made gas diffusion layers (GDLs). The CCM, with an active area of 3 cm  $\times$  3 cm, had a 5 mg cm<sup>-2</sup> PtRu loading at the anode, a Nafion<sup>®</sup> 115 membrane, and a 5 mg cm<sup>-2</sup> Pt loading at the cathode. The GDL was made by coating a micro porous layer (MPL), with 30% PTFE content and 2 mg cm<sup>-2</sup> carbon loading, on a piece of 50% PTFE wet-proof treated carbon cloth from Clean Fuel Cell Energy. Before conducting the tests, the new MEA was activated by discharging at 0.3 V and 60 °C for 24 h in an active DMFC frame. During the MEA activation, 1 M methanol solution and air were fed at the flow rates of 4 ml min<sup>-1</sup> and 100 ml min<sup>-1</sup>, respectively.

### 2.2. Working principle

The working principle of the DMFC fed with neat methanol is similar to that described by Xu et al. [21]. The fuel cell operates passively at room temperature with neat methanol in the fuel reservoir. During stable operation, neat liquid methanol diffuses through the methanol barrier layer, is vaporized by the vaporizer, then flows through the perforated cover, and finally mixes with the generated carbon dioxide and water vapor coming from the cathode side in the gas mixing layer. The methanol vapor and water vapor mixture flows through the anode current collector and reacts at the anode catalyst layer (ACL). At the same time at the cathode, oxygen transports from the atmosphere through the cathode perforated cover to the cathode side of the MEA and reacts at the cathode catalyst

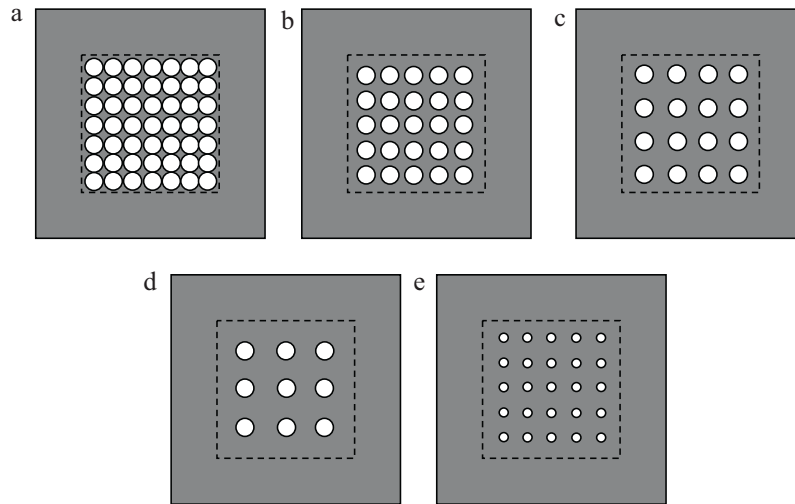


Fig. 2. Perforated covers with open ratios of (a) 38%, (b) 20%, (c) 12%, (d) 7%, and (e) 5%.

layer (CCL). The water generated in the cathode reaction is transported from the CCL, through the Nafion membrane and ACL, to the gas mixing layer on the anode side by liquid pressure gradient and dilutes the methanol vapor coming from the anode vaporizer. In this work, it is going to be tested that the cell performance can be improved by simply changing the anode and cathode open ratios.

### 2.3. Cell test

The current, voltage, power, and resistance of the fuel cell were measured using the Compact Fuel Cell Test system (Model 850C) from Scribner Associates, Inc. The cell performance was evaluated by the commonly used voltage–current density, internal resistance–current density, and power density–current density curves. Each of these results was produced by scanning the voltage from open circuit voltage to 0.05 V and the corresponding voltage, current density, power density, and internal resistance were recorded. After each initial voltage–current density scan, the cell, filled with 2 ml of neat methanol, was discharged at a constant voltage of 0.2 V at room temperature,  $25 \pm 1^\circ\text{C}$ , and ambient humidity, 25–50%, until the discharging current reduced to zero, and all the methanol has been consumed. The fuel efficiency,  $\eta$ , was determined based on the constant voltage discharge as follows [22]:

$$\eta = \frac{\text{Reacted methanol(g)}}{\text{Supplied methanol(g)}} = \frac{M_{\text{MeOH}} \cdot \int_0^T i(t) dt / 6F}{m_{\text{MeOH, sup}}} \quad (1)$$

where  $t$  is the time of the discharging process,  $M_{\text{MeOH}}$  is the molecular weight of methanol,  $T$  is the total discharging time,  $i(t)$  represents the transient discharging current density,  $F$  is the Faraday's constant, and  $m_{\text{MeOH, sup}}$  is the mass of methanol supplied to the fuel reservoir.

## 3. Results and discussion

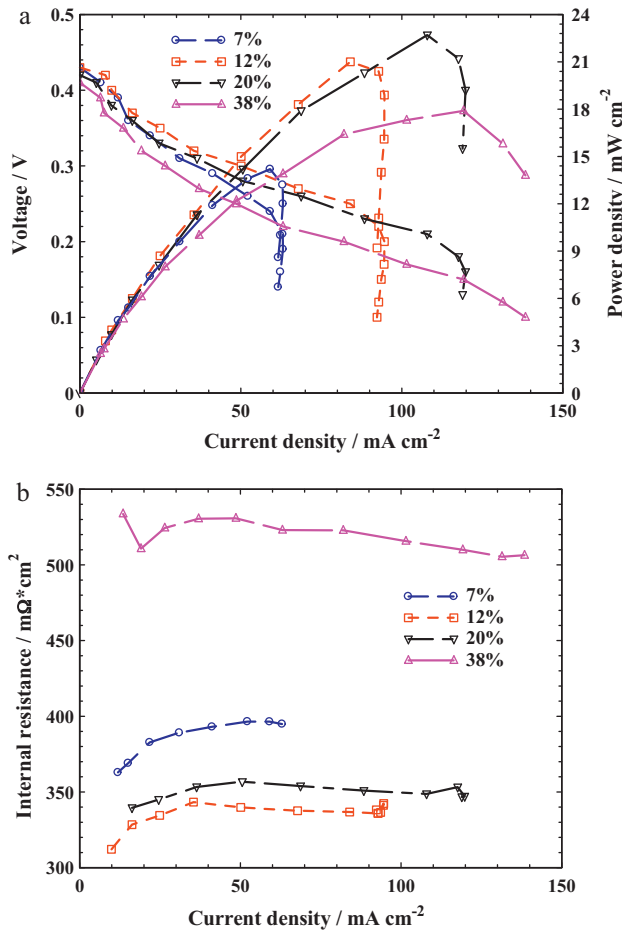
As discussed above, the anode mass transfer resistances should be increased to decrease the methanol crossover, and the cathode mass transfer resistances should be increased to improve the water management. The simple analysis in Appendix A shows that the mass transfer resistances can be increased by using porous materials with lower permeability, or increasing the thickness of a given porous material, or decreasing the open ratio of the porous materials. However, the permeability of the porous material, which is related to its pore size distribution, porosity, and tortuosity, cannot be easily changed unless its manufacture processes are changed.

Increase of the thickness will increase the weight, volume, and cost of the fuel cell system. Among these methods, decrease of the open ratio of the porous material is easy to implement and will not increase the weight and cost of the fuel cell. The effects of cathode open ratio and the open ratio of vaporizer on the performance of a vapor-feed passive DMFC fed with neat methanol have been studied. Combinations of various vaporizers with open ratios ranging from 5% to 100% and cathode open ratios ranging from 5% to 100% have been tested in this experiment. Nevertheless, the cell performance was either non-repeatable or unacceptably bad when the open ratio of the vaporizer was out of the range of 5–20% and the cathode open ratio was out of the range of 7–38%. To clarify the results, the open ratio of the vaporizer varies from 7% to 38% and the open ratio of the cathode varies from 5% to 20% in the following discussions.

### 3.1. Effect of the cathode open ratios

For a fixed anode vaporizer with the open ratio of 12%, the passive DMFC with various cathode open ratios, 7%, 12%, 20%, and 38% was tested, and the current–voltage, current–power density, and current–internal resistance curves are compared in Fig. 3. As can be seen from Fig. 3(a), the limiting current density increased from 61.6 to 92.3, and to 118.9  $\text{mA cm}^{-2}$  and the peak power density increased from 14.2 to 21.0, and to 22.7  $\text{mW cm}^{-2}$  when the cathode open ratio increased from 7% to 12%, and to 20%, respectively. However, when the cathode open ratio was further increased to 38%, the limiting current density increased to 138.4  $\text{mA cm}^{-2}$  while the peak power density decreased to 17.9  $\text{mW cm}^{-2}$  due to higher methanol crossover.

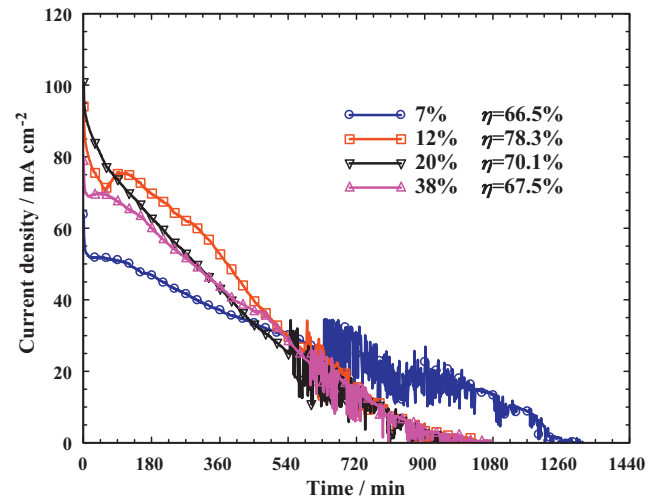
For the case of a low cathode open ratio, such as 7%, the mass transfer resistances of both water vapor and oxygen were high. The insufficient oxygen supply from the cathode side resulted in low limiting current densities and low voltage at high current density regions. As a result, the limiting current density increased as the cathode open ratio increased from 7% to 38%. On the other hand, when the cathode open ratio was high, such as 20% and 38%, although the oxygen supply rate was sufficient, more water vapor was lost from the cathode side to the ambient air. A high water loss rate decreased the water back flow from the cathode to the anode and resulted in an increased methanol crossover, which is also proven by some modeling work [27,28]. As a result, the working voltage decreased from 0.25 to 0.24, and to 0.20 V at a current density of 90  $\text{mA cm}^{-2}$  when the cathode open ratio increased from



**Fig. 3.** Performance of a DMFC operated at room temperature with neat methanol, an anode open ratio of 12%, and various cathode open ratios (7%, 12%, 20%, and 38%) represented by (a) current density vs. voltage and power density and (b) current density vs. internal resistance.

12% to 20%, and to 38%, respectively, as is shown in Fig. 3(a). At the same time, less water was available to hydrate the electrolyte membrane and the internal resistance increased from 337 to 351, and to 523 mΩ cm<sup>2</sup> at the current density of 90 mA cm<sup>-2</sup> when the cathode open ratio increased from 12% to 20%, and to 38%, as is shown in Fig. 3(b). The combined effects of increasing oxygen supply and increasing water loss resulted in a decrease of peak power density when the cathode open ratio was increased from 20% to 38%.

The effect of the cathode open ratios on the fuel efficiency was tested by discharging fuel cells at 0.2 V with 2 ml of neat methanol. The corresponding fuel efficiencies were calculated with Eq. (1) and are compared in Fig. 4. As is seen in Fig. 4, the fuel efficiency significantly increased from 66.5% to 78.3% when the cathode open ratio increased from 7% to 12%. As a result of increasing the cathode open ratio, both the discharging current density and the water generation rate at the cathode increased. More water accumulated at the cathode side and increased the cathode liquid pressure, which increased the water back flow rate and decreased the methanol crossover with an increase in the cathode open ratio from 7% to 12%. However, the fuel efficiency decreased from 78.3% to 70.1%, and to 67.5% when the cathode open ratio was further increased from 12% to 20%, and to 38%. As discussed above, since more water was lost from the cathode to the atmosphere with a larger cathode open ratio, the methanol crossover increased and, subsequently, the fuel efficiency decreased as the cathode open ratios increased to 20% and 38%.



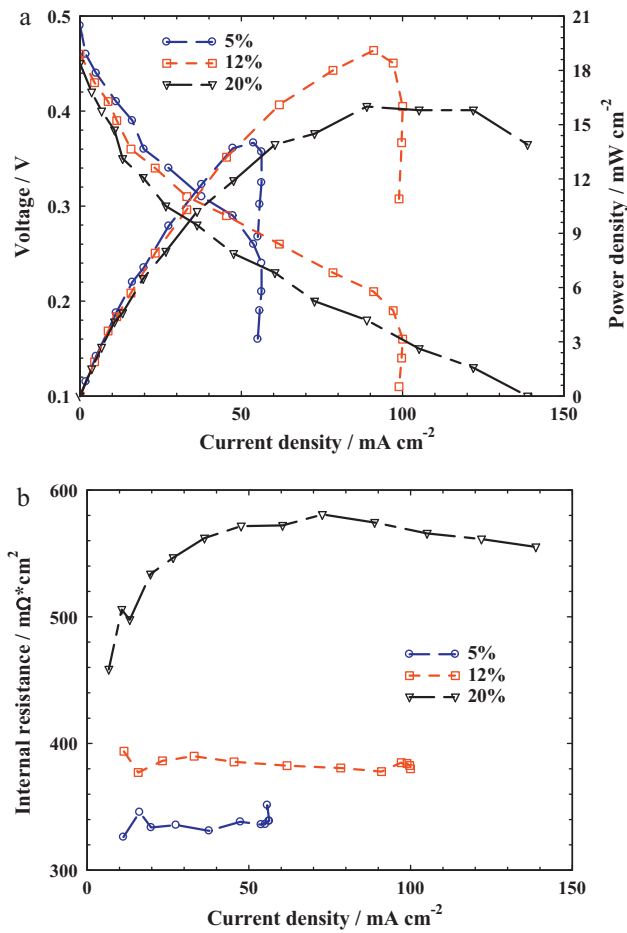
**Fig. 4.** Variations in current density with time during discharge at 0.2 V and room temperature with 2 ml of neat methanol, an anode open ratio of 12%, and various cathode open ratios (7%, 12%, 20%, and 38%).

### 3.2. Effect of the open ratios of anode vaporizer

In our previous work [21], when neat methanol was fed into the fuel cell, the peak power density of the fuel cell kept increasing when the open ratio of the vaporizer decreased from 100% to 28%, and then to 12%. The goal of this work is to find an optimized open ratio of the vaporizer that provides the highest peak power density during neat methanol operation. The DMFC performance with a 20% cathode open ratio and vaporizer with various open ratios of 5%, 12%, and 20% were tested. The corresponding current–voltage, current–power density, and the current–internal resistance curves are compared in Fig. 5.

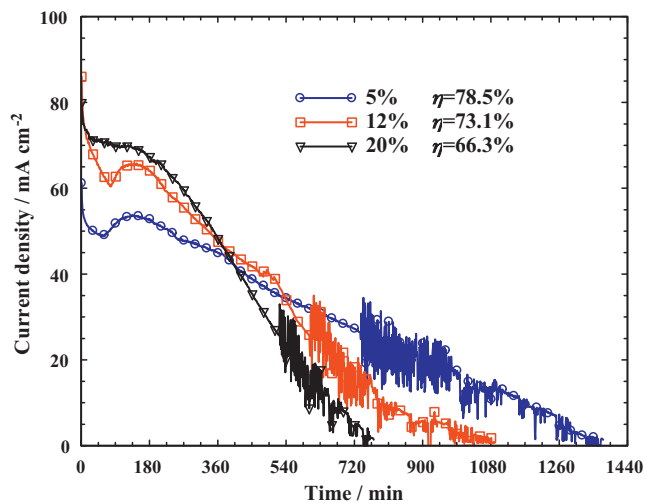
As is seen in Fig. 5(a), the maximum current density decreased from 138.7 to 100.0 mA cm<sup>-2</sup> and the peak power density increased from 16.0 to 19.1 mW cm<sup>-2</sup> when the open ratio of the vaporizer decreased from 20% to 12%. Since the mass transfer resistance from the anode tank to the anode gas mixing layer was increased by decreasing the open ratio of the vaporizer, the methanol supply rate from the tank was lower. Consequently, the methanol concentration in the anode gas mixing layer was decreased, and the methanol crossover and limiting current density were decreased by decreasing the open ratio of the vaporizer. However, by further decreasing the vaporizer open ratio to 5%, the mass transfer resistance was so high that the methanol supplied from the anode tank was insufficient. As a result, the limiting current density significantly decreased from 100.0 to 56.3 mA cm<sup>-2</sup>, which decreased the peak power density from 19.1 to 14.0 mW cm<sup>-2</sup>. Decreasing the open ratio of the vaporizer also caused a decrease in the internal resistance, because less water penetrated through the anode vaporizer into the tank, and more water was trapped in the membrane. Consequently, the proton conductivity of the electrolyte membrane was higher with better hydration. As is shown in Fig. 5(b), by decreasing the open ratio of the vaporizer from 20% to 12%, and to 5%, the internal resistance decreased from 572 to 383, and to 336 mΩ at the current density of 60 mA cm<sup>-2</sup>.

To quantitatively study the effect of the vaporizer open ratio on the methanol crossover, DMFCs with 20% cathode open ratio and vaporizers with different open ratios were discharged at 0.2 V in room temperature with 2 ml of neat methanol. The variations of current density with time are compared in Fig. 6, and the corresponding fuel efficiencies have been calculated. As is seen in Fig. 6, during the first 6 h, the current density was higher for a vaporizer with larger anode open ratio, because the methanol supply rate

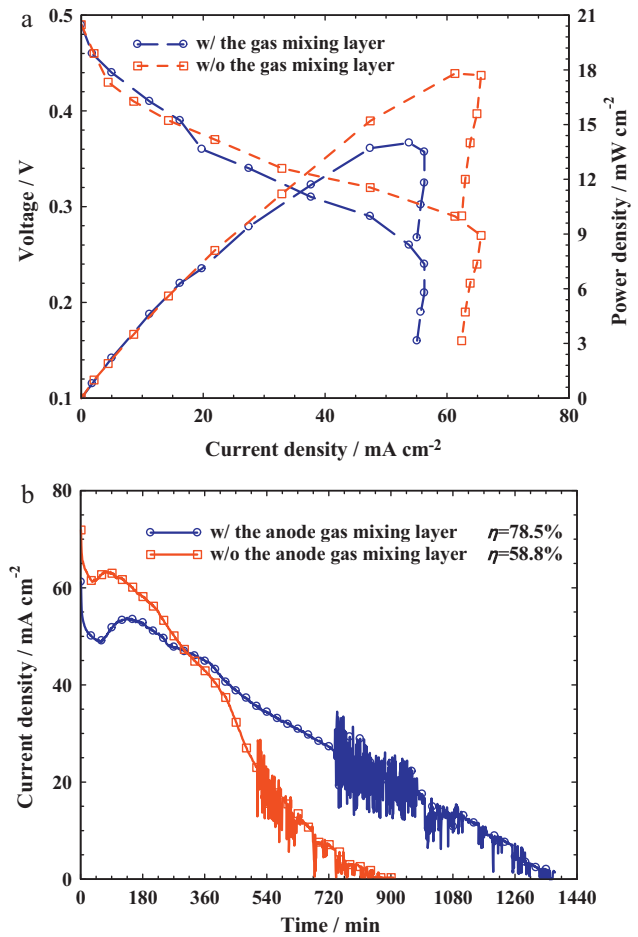


**Fig. 5.** Performance of a DMFC operated at room temperature with neat methanol, a cathode open ratio of 20%, and various anode open ratios (5%, 12%, and 20%) represented by (a) current density vs. voltage and power density and (b) current density vs. internal resistance.

was higher. During the discharge, the water vapor in the anode gas mixing layer could penetrate through the vaporizer to the fuel reservoir by concentration gradient and dilute the methanol. Since the methanol consumption rate was higher with a vaporizer hav-



**Fig. 6.** Variations in current density with time during discharge at 0.2 V and room temperature, with 2 ml of neat methanol, a cathode open ratio of 20%, and various anode open ratios (5%, 12%, and 20%).



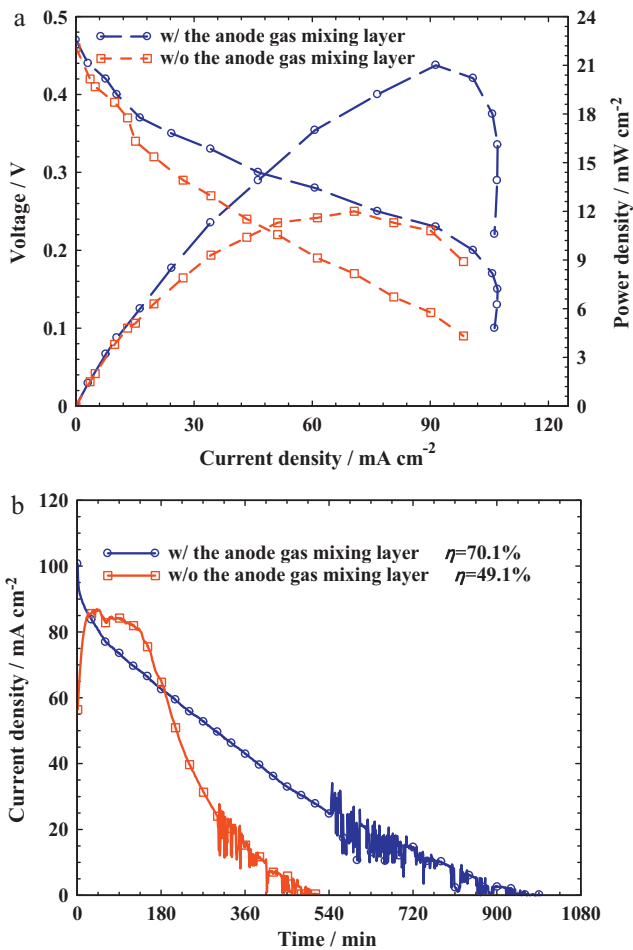
**Fig. 7.** Performance of the passive DMFC with and without the anode gas mixing layer for operation at room temperature with neat methanol, 5% anode open ratios, and 20% cathode open ratios represented by (a) current density vs. voltage and power density and (b) variations of current density with time during the discharge at 0.2 V.

ing larger open ratio, the methanol concentration in the reservoir and, subsequently, the current density, decreased faster. The overall fuel efficiencies, shown in Fig. 6, decreased from 78.5% to 73.1%, and to 66.3% when the vaporizer open ratio increased from 5%, to 12%, and to 20%.

### 3.3. Effect of the anode gas mixing layer

To study the effect of the anode gas mixing layer, the performance of the DMFC with a 20% cathode open ratio and vaporizers with various open ratios were tested after removing the anode gas mixing layer. The effect of the anode gas mixing layer in the DMFC with a vaporizer having 5% open ratio and a 20% cathode open ratio is shown in Fig. 7. As is seen in Fig. 7(a), the cell performance slightly increased by removing the gas mixing layer: the limiting current density increased from 56.3 to 65.6 mA cm<sup>-2</sup>, and the peak power density increased from 14.0 to 17.8 mW cm<sup>-2</sup>. Since the mass transfer resistance of a vaporizer with a 5% anode open ratio was so high, the methanol supply rate from the fuel reservoir was low and the methanol crossover was not an issue. By removing the anode gas mixing layer, the methanol transport from the fuel reservoir to the MEA, as well as the limiting current density and the peak power density increased. On the other hand, the fuel efficiency decreased from 78.5% to 58.8% when the anode gas mixing layer was removed.

The performances of the DMFC with and without a gas mixing layer were tested for a vaporizer with the open ratio of 12%



**Fig. 8.** Performance of the passive DMFC with and without the anode gas mixing layer for operation at room temperature with neat methanol, 12% anode open ratios, and 20% cathode open ratios represented by (a) current density vs. voltage and power density and (b) variations of current density with time during the discharge at 0.2 V.

and a cathode open ratio of 20% and are compared in Fig. 8. As is seen in Fig. 8(a), the cell performance decreased by removing the anode gas mixing layer: the limiting current density decreased from 107.1 to 98.4 mA cm<sup>-2</sup> and the peak power density decreased from 21.0 to 12.0 mW cm<sup>-2</sup>. For a vaporizer with the open ratio of 12%, the methanol supply rate from the fuel reservoir was higher, which resulted in both a higher limiting current density and a higher methanol crossover rate. As a result, the peak power density decreased after removing the anode gas mixing layer. The increase in methanol crossover also caused the fuel efficiency to decrease, as shown in Fig. 8(b). The fuel efficiency decreased from 70.1% to 49.1% by removing the anode gas mixing layer. Moreover, the effect of the anode gas mixing layer was more significant when the open ratio of the vaporizer increased from 5% to 12% by comparing Figs. 7(a) and 8(a). This is due to the fact that more carbon dioxide was generated at a higher current density, thus proving that the gas mixing layer played a more important role when the anode open ratio was 12%.

#### 4. Conclusions

In a DMFC fed with neat methanol, the mass transfer properties of the fuel cells are critical in decreasing the methanol crossover and improving the water management. In this paper, perforated covers with different open ratios were added to the cathode of a passive

DMFC fed with neat methanol to improve its water management without increasing the cell volume or weight. Also the open ratio of the vaporizer was changed to control the methanol crossover in the DMFC. The effects of the cathode open ratios and the vaporizer open ratio on the performance of a passive DMFC fed with neat methanol showed that:

- (1) The water management of the fuel cell could be improved simply by decreasing the open ratio at the cathode side to reduce the water loss from the cathode side and increase water back flow from the cathode to the anode. At the room temperature of  $25 \pm 1$  °C and ambient humidity of 25–50%, a cathode open ratio of 20% was preferred to ensure both a sufficient oxygen supply from the ambient air and small water loss to achieve the highest peak power density.
- (2) Methanol crossover can be reduced by decreasing the open ratio of the vaporizer to increase the mass transfer resistance of methanol from the fuel reservoir to the ACL. A vaporizer with the open ratio of 12% was preferred to ensure both a sufficient methanol supply and lower methanol crossover to achieve the highest peak power density and high fuel efficiency.
- (3) When the vaporizer open ratio was 12%, and the cathode open ratio was 20%, the passive DMFC fed with neat methanol achieved a peak power density of 22.7 mW cm<sup>-2</sup> and a fuel efficiency of 70.1% at room temperature of  $25 \pm 1$  °C and ambient humidity of 25–50%.
- (4) The gas mixing layer at the anode side could decrease the methanol crossover, improve the cell performance, and increase the fuel efficiency. The effect of the gas mixing layer was more important during high current density operation because more carbon dioxide gas was generated at a higher current density.

#### Acknowledgement

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#### Appendix A.

The absolute flux of species  $i$ ,  $\mathbf{n}_i$ , is related to both the diffusive flux,  $\mathbf{j}_i$ , and the convection due to the motion of species  $i$  with the mass-average motion of the mixture,  $V$  [29,30]:

$$\mathbf{n}_i = \mathbf{j}_i + m_i V. \quad (\text{A-1})$$

##### A.1. Diffusive mass transfer resistance:

According to Fick's law of diffusion, the diffusive mass flux of species  $i$  in a porous media is defined as:

$$\mathbf{j}_i = -\rho D_i^{\text{eff}} \nabla m_i, \quad (\text{A-2})$$

where  $m_i$  is the mass fraction of species  $i$ , and the effective diffusivity of the species in a porous media,  $D_i^{\text{eff}}$ , is related to the diffusivity of the species and the porosity of the porous media [31,32]:

$$D_i^{\text{eff}} = D_i \varepsilon^{1.5}. \quad (\text{A-3})$$

Defining the mass transfer resistance as the ratio of a driving potential to the corresponding transfer rate, it follows from Eq. (A-2) that the diffusive mass transfer resistance of a plane porous media is [29]:

$$R_{\text{diff}} \equiv \frac{\Delta m_i}{A \cdot \mathbf{j}_i} = \frac{\delta}{A \cdot \rho \cdot D_i \varepsilon^{1.5}}. \quad (\text{A-4})$$

where  $\delta$  is the thickness of the porous media. By changing the thickness of the porous media to  $\delta'$ , the diffusive mass transfer resistance is increased by  $n_{\text{diff}}$  times:

$$n_{\text{diff}} = \frac{\delta'}{\delta}. \quad (\text{A-5})$$

On the other hand, if the open ratio of the porous media is decreased, while its thickness remains unchanged, the resistance to diffusive mass transfer is increased to:

$$R''_{\text{diff}} = \frac{\delta}{\phi A \cdot \rho \cdot D_i \varepsilon^{1.5}}, \quad (\text{A-6})$$

where  $\phi$  is the open ratio of the porous media, and the value of  $\phi$  is between 0 and 1. The diffusive mass transfer resistance is increased by  $n_{\text{diff,OR}}$  times:

$$n_{\text{diff,OR}} = \frac{R''_{\text{diff}}}{R_{\text{diff}}} = \frac{1}{\phi}. \quad (\text{A-7})$$

#### A.2. Convective mass transfer resistance

The bulk motion of fluids in the porous media,  $V$ , can be determined by Darcy's Law. Assuming the porous media is isotropic, and the effect of gravitational force is negligible, the velocity of the fluid,  $V$ , is determined by the pressure gradient only [30]:

$$\mathbf{V} = -\frac{K}{\varepsilon \mu} \nabla p, \quad (\text{A-8})$$

where  $K$  is the permeability of the porous media,  $\varepsilon$  is the porosity of the porous media, and  $\mu$  is the viscosity of the fluid. The convective mass transfer resistance due to convection through a plane porous media is:

$$R_{\text{conv}} \equiv \frac{\Delta p}{A \cdot \mathbf{V}} = \frac{\varepsilon \mu \delta}{A \cdot K}. \quad (\text{A-9})$$

By increasing the thickness of the porous plate to  $\delta'$ , the convective mass transfer resistance is increased by  $n_{\text{conv}}$  times:

$$n_{\text{conv}} = \frac{\delta'}{\delta}. \quad (\text{A-10})$$

On the other hand, if the open ratio of the porous media is decreased, while its thickness remains unchanged, the convective mass transfer resistance is increased to:

$$R''_{\text{conv}} = \frac{\varepsilon \mu \delta}{\phi A \cdot K}, \quad (\text{A-11})$$

where  $\phi$  is the open ratio of the porous media, and the mass transfer has been increased by  $n_{\text{conv,OR}}$  times:

$$n_{\text{conv,OR}} = \frac{R''_{\text{conv}}}{R_{\text{conv}}} = \frac{1}{\phi}. \quad (\text{A-12})$$

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