Experimental study on anode components optimization for direct glucose fuel cells

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Abstract
Membrane electrode assemblies, as the core component, mainly determine the overall performance of fuel cells. As a part of it, the anode electrode is vitally important for the mass transportation and electrochemical reaction. To gain a high cell performance, the structures of the anode electrode are designed by optimizing the component parameters of the micro-porous and catalyst layers. The effect of polytetrafluoroethylene (PTFE) content in anode micro-porous layer and catalyst loading in catalyst layer on electrode resistance and electrochemical performance are investigated. The current collection effect affected by the carbon loading of micro-porous layer is analyzed, and the influence of catalyst binder on the fuel electrolyte transportation performance has been explained from the aspects of microscopic morphology. The experimental results show that the resistance of anode micro-porous layer can be decreased significantly by loading carbon black powder and PTFE with optimal contents on the micro-porous layer. As compared with the I2 anion-ionomer, the fuel electrolyte transportation can be facilitated by applying PTFE-bonded anode catalyst layer due to the richer micro-pores and larger specific surface area. In addition, there is an optimal anode catalyst loading of 1.7 mgPd cm$^{-2}$ to achieve the highest peak power density of 11.5 mW cm$^{-2}$ at 60 °C.

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1. Introduction

Nowadays, glucose is gaining increasingly attentions as one of the most promising alternative energy sources because of its advantages of high theoretical energy density (4430 Wh kg$^{-1}$), environment-friendly, rich in nature plants and industrial processes. Among the ways of energy utilization [1–3], the method of direct conversion of the chemical energy in glucose to electrical energy is undoubtedly the most efficient one. Therefore, the glucose fed direct liquid fuel cell has received considerable attentions in the recent years. Biofuel cells (BFCs) including the enzymatic biofuel cell and the microbial fuel cell that use enzyme and microorganism as the anode catalysts, can complete oxidizing glucose to CO2 with 24 electrons generation [4]. Enzyme, such as glucose oxidase and glucose dehydrogenase, is directly employed by the enzymatic biofuel cell, which has high catalyst efficiency in glucose oxidation. However, the short operating durability caused by the instability of enzymes mainly impedes the application of the enzymatic biofuel cell [5]. The microbial fuel cell (MFC) possesses the advantage of relatively long-term durability because of its stable activity under complex operating environment; a lot of works have been done for a higher output power [6–9]. Nevertheless, the bacterial chemical kinetics, the complex transmission of mass and electrons still limit the output power of the MFC [10,11].

To overcome the above listed complicity and shortcomings of the biofuel cells, particular attentions have been paid to the nonenzymatic direct glucose fuel cell (DGFC), in which the metal nanoparticles are used as catalyst to oxide the glucose in the anode electrode [12]. According to Brouzgou and Tsiakaras [13], the metal nanoparticles catalyzed DGFCs exhibited superior performance in the alkaline medium compared with it in the acidic electrolyte because of the boosted electrochemical reaction kinetics of both anode and cathode reactions. Fujiwara et al. [14] demonstrated the
superiority of alkaline fuel cell by comparing the performance of cation exchange membrane (CEM) DGFC with that of anion exchange membrane (AEM) DGFC. Platinum ruthenium (Pt–Ru) and platinum (Pt) were used as the cathode and anode catalysts. The results revealed that the peak power density can be significantly improved from 1.5 mW cm$^{-2}$ to about 20.0 mW cm$^{-2}$ by changing from CEM-DGFC to AEM-DGFC. The advantages of the alkaline DGFC are as follows: 1) When the alkaline dissolves in the fuel solution, the reactant-delivering pathway also plays a role of ion-conducting pathway, resulting in an enlarged triple-phase boundary, where electrochemical reaction takes place; 2) According to the schematic of the alkaline AEM-DGFC as shown in Fig. 1. OH$^-$ is transferred from cathode electrode to anode electrode. This electro-osmotic drag can reduce the penetration of fuel from anode to cathode effectively, which makes an improvement on the cell performance; 3) Non-noble metals can also be used as the electro-catalysts to gain a good cell performance because of the accelerated redox kinetics in alkaline solutions [15]. In this case, the cost of the fuel cell can be much lower by replacing the platinum with palladium as the electrochemical catalyst [16].

According to the reaction scheme in the alkaline medium, because of the stable molecular structure of glucose, only two electrons will be released during the glucose oxidation to gluconic acid process, which limits the performance of DGFC to a much lower level than the theoretical energy density [17,18]:

Anode: $\text{C}_6\text{H}_{12}\text{O}_6 + 2\text{OH}^- \rightarrow \text{C}_6\text{H}_{12}\text{O}_7 + \text{H}_2\text{O} + 2e^-$ (1)

Cathode: $1/2 \text{O}_2 + \text{H}_2\text{O} + 2e^- \rightarrow 2\text{OH}^-$ (2)

Overall: $\text{C}_6\text{H}_{12}\text{O}_6 + 1/2 \text{O}_2 \rightarrow \text{C}_6\text{H}_{12}\text{O}_7 + \text{H}_2\text{O}$ (3)

Many efforts have been made to improve the efficiency of glucose electro-oxidation by employing the metal nanoparticles-based electro-catalysts. One method to promote the anode electrode performance is to use metal nanoparticle catalysts to increase the electrochemical activity sites and to reduce the influence of intermediate products on the catalysts. For instance, the noble metal based catalysts, such as Pt [19], Au [20], bi-metallic catalysts of Pt–Au, Pt-Bi [21] are reported for glucose electro-oxidation in alkaline medium. With the aid of these superior electro-catalysts, an active and stable glucose electro-oxidation process can be obtained. Another method to promote the anode electrode performance is that the electrodes with modified carbon substrates, such as the reduced graphene oxide [22] and carbon nanotubes [23] are used as catalyst supports, which have been found to exhibit excellent electro-catalytic activity. Li and He [24] loaded the Pd-based nanocatalysts on a novel honeycomb-type carbon foam by using a layer-reduction method to boost the catalytic activity and stability. By employing the carbon substrates with large specific area, the catalyst particles can be dispersed homogeneously and the mass transfer resistance can be reduced alongside. It must be pointed out that the cell performance is closely related to the electrons and mass transmission processes between the porous layers of the DGFC. Li and Zhao [25] investigated the effect of cathode structure on the transportation of water and gas in alkaline liquid fuel cell. They found that the added hydrophobic layer is beneficial to the cathodic water transportation and the content and type of carbon substrates in the micro-porous layer have significant impacts on the cathode potential. Thus, the optimization of electrode structure is another effective method to reduce the mass transfer resistance and to improve the cell performance. For a DGFC with glucose as the fuel, it is especially beneficial for a smooth mass transportation between the porous layers on account of the high viscosity and large molecules factors of glucose. Based on the literature review, it appears that there are not many studies related to the effect of the anode structure on the performance of DGFC.

In this paper, the optimization of anode electrode structure is carried out on the components of catalyst layer (CL) and the micro-porous layer (MPL). Based on our previous work [26], the influence of carbon contents in the MPL on the current collection is further analyzed. The microscopic morphology of anode CL is used to explain how the catalyst binders affects the transportation of fuel electrolyte. In addition, the effects of content ratio of PTFE to carbon black powder in MPL and catalyst loading in CL on cell performance are investigated. This paper is organized as follows. In Section 2, membrane electrode assemblies (MEAs) with varying components of anode electrodes are fabricated and installed into the DGFCs. In Section 3, the influence of the PTFE content, the carbon black powder content in the micro-porous layer, the catalyst binders, and catalyst content in the catalyst layer are investigated experimentally to obtain a weaken mass and electrons transfer resistance. Section 4 concludes with findings.

2. Experiment

The primary objective of this paper is to improve the performance of the DGFC by the optimized anode electrode structure. Four MEAs with different content ratios of PTFE to carbon black powder in the anode MPL were prepared, named as MEA-1 to MEA-4. In addition, MEA-5 to MEA-8 with different contents of carbon black powder loaded in the anode micro-porous layer were prepared. I2 ionomer and PTFE were used as the anode catalyst binders in MEA-9 and MEA-10, respectively. In MEA-11 to MEA-14, catalyst nanoparticles with different contents were loaded on to the anode catalyst layer respectively. After that, the fuel cells with these prepared MEAs were assembled and tested electrochemically and physicochemically.

2.1. Chemicals and reagents

Carbon paper (HCP010, Shanghai Hesen Electric Co. Ltd., 0.1 mm) used as the support layer was treated by PTFE in order to get a hydrophobic property. Carbon black powder (Vulcan XC-72R) and polytetrafluoroethylene (PTFE) solution (60 wt%, Hesen, Shanghai, China) was used as the levelling layer to make a smooth surface of carbon paper in the micro-porous layer. Pd/C (30 wt% of
palladium content) was offered by the Sigma Aldrich for the anode and cathode catalysts preparation. I2 alkaline ionomer with good conductivity and exceptional binding properties was developed and patented by Acta S.P.A. The α-gulose (Tianjin Kemiou Chemical Reagent Co. Ltd.), potassium hydroxide (≥85 wt%) (Sichuan Xilong Chemical Co. Ltd.) and ethanol (≥99.7 wt%) (Guangdong Guanghua Sci-Tec Co. Ltd.) were used as fuel, electrolyte and solvent, respectively, which were all analytical grade. Ultrapure water (18.25 MΩ cm⁻¹ Millipore-Milli-Q) was used to prepare all the aqueous solutions in this work.

2.2. Preparation of membrane electrode assembly

During the MEA fabrication, the anode and cathode electrodes were separated by the AEM (A201), provided by Tokuyama. In the preparation of the anode electrode of MEA-1 to MEA-4, 1.5 mg cm⁻² of carbon black powder and 10 wt% to 40 wt% of PTFE (the quality of PTFE in the levelling layer) were first mixed in the ethanol solvent solution with the ultrasonically stirring around 40 min until they were well dispersed. The mixture solutions were then brushed on to the carbon papers in sequence, which were used as the microporous layers. In case of the catalyst agglomeration in the preparation process of catalyst slurry, the mixture of Pd/C catalyst particles, 5 wt% of I2 ionomer as the binder and ethanol solvent solution was ultrasonically stirred in the ice water for about 20 min. The anode CL was then formed by spraying the prepared catalyst slurry (Pd/C) on the AEM to obtain the catalyst layers of MEA-1 to MEA-4, in which the anode catalyst loading was 1.0 mgPd/cm².

The carbon black powder with loading of 0, 0.3, 0.6 and 0.9 mg cm⁻² and 20 wt% PTFE were used respectively as the microporous layer of MEA-5 to MEA-8. Pd/C (2.0 mgPd/cm²) and I2 alkaline ionomer (30 wt%) were loaded on the AEM, which were used as the catalyst layer of MEA-5 to MEA-8.

I2 ionomer and PTFE were used to bond the catalyst particles in the anode catalyst layers of MEA-9 and MEA-10 respectively, on which the same 1.7 mgPd/cm² Pd/C was loaded on the MPL, which were used as the catalyst layer of MEA-5 to MEA-8. I2 ionomer and PTFE were used to bond the catalyst particles in the anode catalyst layers of MEA-9 and MEA-10 respectively, on which the same 1.7 mgPd/cm² Pd/C was loaded on the MPL to form the catalyst layer. In addition, Pd/C with loading of 1.0, 1.4, 2.2 and 3.0 mgPd/cm² were incorporated into the anode catalyst layer of MEA-11 to MEA-14 in sequence.

For the cathode electrodes of all the fourteen MEAs, the carbon papers with carbon black powder (1.5 mg cm⁻²) and PTFE (40 wt%) were acted as the cathode micro-porous layer. Finally, Pd/C (1.2 mgPd/cm²) and PTFE (5 wt%) were brushed on the MPL forming the CL.

2.3. Fuel cell fabrication

The prepared MEA were assembled between the anode and cathode current collectors, as shown in the detail view profile of Fig. 2. The gaskets between the MEA and current collectors were used to prevent the short-circuit and seal the fuel of the anode and oxygen of the cathode. The serpentine flow channels with a width of 0.8 mm and a depth of 0.6 mm were engraved on the stainless-steel current collectors. The width of the rib between two adjacent flow channels is 0.8 mm. The fuel stream and gas were transported from the channels to the MEA. The effective reaction area of the MEA is 1.0 cm × 1.0 cm. The thermocouple and electrical heating rod are fixed on the stainless-steel plates to control the cell operating temperature.

2.4. Electrochemical and physicochemical tests

The electrochemical measurement system is shown in Fig. 2. The prepared fuel electrolyte mixture (0.5 mol/L glucose and 2.0 mol/L KOH) with a flow rate of 1.5 mL min⁻¹ was transferred by the peristaltic pump (LONGERPUMP BT100-1F) from the fuel tank to the anode. The gas flowmeter (Omega FMA-765A-V) was used to transfer oxygen to the cathode at a stable volumetric flow rate of 50 mL min⁻¹. The operation temperature was maintained at 60 °C by the temperature controller. The ohmic resistance of electrode was measured by utilizing a home-made fixture (with a resistance of 44 mΩ) [7]. In the fixture, the electrode was tightened between a pair of stainless steel disks (with an area of 1 cm²). The resistance can be measured by the electrochemical workstation connecting with the fixture. The electrochemical active surface area (EASA) was measured by the cyclic voltammetry (CV) experiment of three-electrode cell assembly. A catalyst coated anode electrode with an area of 1.0 cm × 1.0 cm was used as the working electrode, a platinum foil was used as the counter electrode and a Hg–HgO electrode (MMO, 1.0 M KOH) was used as the reference electrode. The potential range for CV test is −0.926 V to 0.274 V vs. MMO with the sweep rate of 10 mV s⁻¹ in 1.0 M KOH solution. The electro-discharge process and electrochemical characterization were controlled and tested by the electrochemical workstation (AUTO-LAB PGSTAT302 N).

For the physicochemical characterization of anode of DGFC, the field emission scanning electron microscope (HITACHI SU-8010) was used to study the anode surface morphologies. The specific surface area of the catalyst layer of anode electrode was measured with an automatic gas sorption analyzer (Quantachrome Autosorb IQ).

2.5. Uncertainty analysis

The oxygen flow rate (mflO) was controlled by the gas flow meter with the uncertainty of 1%. The flow velocity of fuel electrolyte (mfl) was controlled by the peristaltic pump with the uncertainty of 2%. The thermocouple is pre-calibrated to measure the temperature of the system (Tcp), and the uncertainty was 0.5%. The discharge current uncertainty of electrochemical workstation (I) was within 0.2%. Based on the uncertainty propagation analysis [27], as shown in Eq. (4), the expanded cell voltage evolution (Ve) uncertainty was calculated to be 2.3%.

\[ \frac{\Delta V_e}{V_e} = \sqrt{\left(\frac{\Delta T_{cp}}{T_{cp}}\right)^2 + \left(\frac{\Delta mfl}{mfl}\right)^2 + \left(\frac{\Delta mfl}{mfl}\right)^2 + \left(\frac{\Delta I}{I}\right)^2} \] (4)

3. Results and discussions

The main role of the micro-porous layer in the MEA is to support the catalyst layer and to provide transport channels for the mass transportation. The thickness of the MPL is one of the major factors that affects the mass transportation process. Thus, in this work, the electrochemical performance of DGFCs with the varying PTFE and carbon content loaded on the anode MPL were investigated first. And then the impacts of the compositions of the anode catalyst layer on the DGFC performance were explored.

3.1. Influence of the PTFE content in anode MPL

The effect of PTFE content ratio to carbon black powder in the anode micro-porous layer on the DGFC performance is investigated. It is shown in Fig. 3, with PTFE content increasing in the anode electrode, the peak power density (PPD) increases first and then decreases. As the PTFE content rising from 10 wt% to 20 wt%, the PPD increases from 5.7 to 5.9 mW cm⁻². However, as the PTFE continues to increase to 30 wt% and 40 wt%, the PPD is decreased to 5.8 and 5.4 mW cm⁻².
The reason can be explained as follows. (1) With the addition of PTFE, the carbon black powder in the anode MPL can be bonded closely so that the surface of MPL becomes smooth, which is helpful for the current collection. (2) As excessive PTFE is loaded, the carbon black powder in the MPL can be bonded densely, and the many micro-pores would be blocked. Therefore, the mass transfer resistance is increased, which can be confirmed by the maximum current density in Fig. 3. With the PTFE content increasing, the maximum current density is decreased monotonically. (3) Due to the insulating property of PTFE, the electrical resistance of MPL will be increased with too much PTFE loaded on it, as shown in Fig. 4. The resistance of anode MPL decreases from 134.2 to 104.5 mΩ cm² with the increased PTFE content from 10 wt% to 20 wt%, which is resulted from the improved performance of current collection. However, with PTFE content continues to increase from 20 wt%, the anode MPL resistance is increased rapidly. The resistances of 176.8 and 195.1 mΩ cm² are obtained when the 30 wt% and 40 wt% PTFE are loaded on the anode MPL. Hence, there exists an optimal PTFE content of 20 wt% to balance the current collection performance and mass transfer resistance.

3.2. Effect of the carbon content in anode MPL

The current-voltage curves of MEA-5 to MEA-8 with carbon loading of anode MPL ranging from 0, 0.3 and 0.6–0.9 mg cm⁻² are vividly presented in Fig. 5(a). When 0.3 mg cm⁻² carbon black powder content is added on the carbon paper, the performance remained the same as MEA-5 in the current range of 0–10.0 mA cm⁻², which is known as the activation polarization region. In the ohmic polarization region of 10–22.0 mA cm⁻², there exists a slight incremental performance of DGFC with the added 0.3 mg cm⁻² carbon black powder. It can be confirmed from the power density curves in Fig. 5(b) that 6.7 mW cm⁻² PPD of MEA-6 is obtained compared with the 6.5 mW cm⁻² PPD of MEA-5. This phenomenon can be attributed to the enlarged area of current collection with coating carbon black powder on the carbon paper. The uneven character of the carbon paper limits its current collection performance. With the carbon black powder coating on the carbon paper, a smooth micro-porous layer is obtained, which is helpful to reduce the electrons transfer resistance. Thus, MEA-6 performs better than MEA-5 in the ohmic polarization region with the aid of the facilitated electrons transportation, which can be confirmed by the resistance of anode MPL. As shown in Fig. 6, with 0.3 mg cm⁻² carbon black powder loaded on, the resistance of anode MPL is decreased rapidly from 130.9 mΩ cm² to 37.2 mΩ cm².

However, when current density continues increases to over 22.0 mA cm⁻², the performance of MEA-6 is lower than that of MEA-5. Moreover, as shown in Fig. 5(b), with the carbon content increasing to 0.6 and 0.9 mg cm⁻², the PDD declines rapidly to 5.9
and 4.4 mW cm\(^{-2}\), respectively. The reason is that the incremental carbon content on the carbon paper also means a thicker micro-porous layer, which leads to a lengthen transfer path of the fuel electrolyte from the flow channel to the CL, which can also be confirmed in Fig. 6. With 0.6 mg cm\(^{-2}\) carbon loading on the anode MPL, the resistance of MEA-7 remains the same as MEA-6. After that, the resistance begins to increase with the carbon black powder continues to be loaded on the anode MPL. The anode MPL resistance is increased sharply from 43.4 m\(\Omega\) cm\(^2\) with 0.9 mg cm\(^{-2}\) carbon loading to 104.5 m\(\Omega\) cm\(^2\) with 1.5 mg cm\(^{-2}\) carbon loading of MEA-2.

On account of the high viscosity and large molecules factors of glucose, a longer diffusion path results in a more severe mass transfer polarization, which can be verified from the maximum current density (MCD) in Fig. 5(a). In the region of concentration polarization, at the same current density, the cell voltage declines persistently with the increased carbon black powder coated on the carbon paper. Thus, the added carbon black powder on the micro-porous layer on one hand can reduce the resistance of electrons transportation, but on the other hand, it can cause a severe transfer polarization of the glucose and electrolyte. Consequently, MEA-6 gives the highest PPD of 6.7 mW cm\(^{-2}\) in ohmic region by loading the optimal carbon black powder content on the anode MPL.

3.3. Influence of the anode catalyst binder types

I2 ionomer and PTFE as binders in the anode catalyst layer of MEA-9 and MEA-10 are used in this work to bond the anode catalytic particles. The influence of the catalyst binders in anode catalyst layer on DGFC performance is investigated. As presented in Fig. 7, the performance of DGFC can be improved prominently when I2 ionomer is replaced by PTFE in the anode CL. Comparing with the 9.6 mW cm\(^{-2}\) PPD and under 80.0 mA cm\(^{-2}\) MCD of MEA-9, 11.5 mW cm\(^{-2}\) PPD and over 80.0 mA cm\(^{-2}\) MCD of MEA-10 are obtained.

The enhanced performance of MEA-10 is attributed to its superior pore distribution in catalyst layer, as evidenced in Fig. 8. The anode catalyst layer micro-pore volume of MEA-10 is higher than that of MEA-9. In anode CL with the strong capillary force of micro-pores, the glucose and electrolyte can be easily absorbed on the catalyst sites. Hence, the transfer resistances of glucose and KOH are reduced due to the increased number of micro-pores in the anode CL with the PTFE binder. Table 1 lists the anode catalyst layer surface area of MEA-9 and MEA-10, which are calculated based on the nitrogen adsorption isotherms. The surface area of PTFE bonded catalyst layer is 69.71 m\(^2\) g\(^{-1}\), which is about 2.5 times of anode CL with I2 ionomer as the binder.

As the SEM images shown in Fig. 9 the anode catalyst nanoparticles are easily agglomerated with I2 ionomer as binder. Amounts of catalyst sites for the electrochemical reaction are in...
Thus, MEA-8 performs better than MEA-7 because of the enlarged triple-phase boundary.

### 3.4. Influence of the anode catalyst loading

The effect of the anode catalyst content on the DGFC performance is also studied by loading 1.0, 1.4, 2.2 and 3.0 mgPd cm$^{-2}$ catalyst on the MEA-11 to MEA-14 anode CL. MEA-10 with 1.7 mgPd cm$^{-2}$ catalyst loading is also tested for comparison. The performances of all these five MEAs are shown in **Fig. 10**. With the increase of catalyst loading in anode electrode from 1.0 to 1.7 mgPd cm$^{-2}$, the PPD increases significantly from 4.4 to 11.5 mW cm$^{-2}$. And then, the DGFC performance decreased slightly with the Pd loading continues increase to 2.2 mgPd cm$^{-2}$. Nevertheless, the PPD decreases remarkably from 11.2 to 7.9 mW cm$^{-2}$ with increasing catalyst content from 2.2 to 3.0 mgPd cm$^{-2}$.

The phenomena that the best DGFC performance is gained by an optimal catalyst coating on the anode CL can be explained by the following two reasons. On one hand, the EASA of the catalyst film is developed with the proper catalyst loading in the anode CL. According to the CV test shown in **Fig. 11**, the anode catalyst EASA can be obtained by determining the of PdO reduction coulombic charge [28]. The EASA is obtained by the following equation:

$$\text{EASA} = \frac{Q}{ql}$$  \hspace{1cm} (5)

where $q$ is the charge value of 4.05 C m$^{-2}$ assumed for the reduction of PdO monolayer and $l$ is the catalyst loading. The relevant results are listed in **Table 2**. With the anode catalyst loading increasing from 1.0 mgPd cm$^{-2}$ to 1.7 mgPd cm$^{-2}$, the electrochemical active surface area of 1 cm$^2$ active area was increased from 18.8 to 28.9 m$^2$ g$^{-1}$.

On the other hand, incremental catalyst content causes the increased thickness of the CL which promotes mass and charge transfer resistance detrimentally. As shown in **Fig. 12**, as the catalyst content increasing from 1.0 mgPd cm$^{-2}$ to 3.0 mgPd cm$^{-2}$, the resistance of anode electrode is increased from 42.3 m$\Omega$ cm$^{-2}$ to 119.4 m$\Omega$ cm$^{-2}$, which means a severe resistance of charge transportation. As shown in **Table 2**, the EASA of anode electrode began to decrease when the anode catalyst loading is greater than 1.7 mgPd cm$^{-2}$. This is because as the catalyst loading increases, catalyst particles are agglomerated more easily, which causes more blocked micro-pores and larger mass transfer resistance. Thus, the cell performance is not proportional to the catalyst loading, and the optimal catalyst loading is about 1.7 mgPd cm$^{-2}$ to obtain the

![Fig. 8. Pore diameter distributions of the anode CL of MEA-9 and MEA-10.](image)

**Table 1**
<table>
<thead>
<tr>
<th>MEA</th>
<th>Binder in the anode CL</th>
<th>Surface area of anode CL</th>
</tr>
</thead>
<tbody>
<tr>
<td>MEA-9</td>
<td>I2 alkaline ionomer</td>
<td>28.21 m$^2$ g$^{-1}$</td>
</tr>
<tr>
<td>MEA-10</td>
<td>PTFE</td>
<td>69.71 m$^2$ g$^{-1}$</td>
</tr>
</tbody>
</table>

![Fig. 9. SEM images of the anode electrode CL with different types of binder: (a–b) I2 ionomer; (c–d) PTFE.](image)
4. Conclusions

In this work, effect of the anode electrode components of alkaline DGFC on cell performance is studied. Improving the cell performance is the main objective that has been analyzed by changing the PTFE content and carbon loading in the micro-porous layer, type of anode catalyst binder, and the anode catalyst loading. By applying the optimal PTFE content and carbon black powder loading in the micro-porous layer, proper catalyst binder and catalyst content, the mass and electron transfer resistances can be reduced and the performance of the DGFC can be improved. The conclusions are summarized as follows:

1. The MEA with the optimal 20 wt% PTFE in the micro-porous layer performs the highest peak power density because of the enlarged current collection area and low mass and electron transfer resistances.

2. The anode electrode with an ultra-thin micro-porous layer that only contains 0.3 mg cm$^{-2}$ carbon black powder gives the best performance among the four anode electrodes with different carbon contents in MPL because of the enhanced electrons transportation.

3. The performance of the MEA with PTFE bonded anode catalyst layer is superior to the MEA with I2 ionomer as binder, since the catalyst particles can be agglomerated with the addition of I2 ionomer in anode CL, which decreases the active surface area. In addition, the glucose and KOH mass transfer can be enhanced by the porous structure of the PTFE bonded anode CL.

4. Among the five MEAs with different catalyst particles loaded on the anode CL, the performance of MEA with 1.7 mgPd cm$^{-2}$ anode catalyst loading is the best. This is because...
the optimal catalyst loading can enlarge the electrochemical active surface area and retain a low mass and charge transfer resistances.

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