INTRODUCTION

Direct liquid fuel cells (DLFCs) whose anode are fed with aqueous reactants are currently studied intensively because of their numerous advantages, such as instant recharging, ease of transport and storage, and high energy density, in contrast with H₂-fed PEMFCs. Although DLFCs use a polymer membrane to separate the anodic and cathodic reactions and transport the ion, fuel crossover from the anode to the cathode degrades the cell performance and remains a challenge.

Using a liquid electrolyte stream by DLFCs to replace the proton exchange membrane might be a promising architecture for DLFCs, since the electrolyte flow between electrodes can prevent the fuel from approaching the cathode, enhance the ionic conductivity, and reduce...
the fuel cell cost. Membraneless fuel cells (MFCs) are generally achieved using a one-pass, single microchannel sandwiched between two face-to-face catalyst layers, and in which two laminar streams, including the anolyte and an electrolyte, flow in parallel. Since the electrolyte stream flows between the fuel and the cathode catalyst layer, the fuel molecules diffused into the electrolyte stream can be carried downstream and then discharged, leading to negligible fuel crossover. Besides commonly used liquid fuels, such as formic acid, methanol, and alcohol, there are still numerous chemicals that can be used as liquid fuel, such as the H2O2, NaBO3, NaBH4, and HCOONa, in acidic or alkaline media. Note that direct formate fuel cells (DFFCs) have recently attracted significant attention and are becoming an emerging energy technology, primarily because they use carbon-neutral fuel with low-cost electrocatalytic and membrane materials. Among those studies, the low catalytic activity of Pt/C for the oxidation of potassium formate was also found. Furthermore, although numerous MFC studies have been published, only a few studies attempted to enlarge the fuel flow field of the MFCs with more complicated fuel cell configuration to produce a higher current density.

Concerning the DLFC performance, besides reducing fuel crossover, the gas diffusion electrode (GDE) for the anode must be specially treated whether the polymer membrane is used or not, because, first, the fuel is required to wet the catalyst layer of the GDE. Second, adequate room in the electrode is necessary to permit the gaseous product (CO2) removal for the case of methanol and formic acid oxidation. Finally, optimal dispersion of the polymer binder must be presented within the catalyst layer to keep the discrete catalyst particle retained and highly porous on the GDE.

Li et al tested alkaline direct ethanol fuel cells (DEFCs) with either an anion-conducting ionomer A3 or a neutral polymer PTFE, presented in the anode catalyst layer. The results showed that the cell performance depended on the A3 ionomer content, when feeding the C2H5OH solution as fuel, whereas the PTFE binder yielded better performance than the A3 binder when feeding the C2H5OH–KOH solution as fuel. Kang et al investigated the effect of Nafion ionomer aggregation state, which can be tuned by heat treatment of Nafion solution, within the anode catalytic layer for a direct formic acid fuel cell. The results showed that the Nafion aggregation decrement within the catalyst ink increased the Nafion ionomer and catalyst utilization. Once the Nafion solution was preheated before coating on the diffusion layer, the Nafion loading within the anode catalyst layer became a minor effect on the cell performance.

An et al synthesized a novel agar chemical hydrogel (ACH) electrode binder to prepare the fuel cell cathode for alkaline-acid DEFC. The results revealed that using the ACH-based cathode in the fuel cell fed with a fuel–electrolyte solution improved the cell performance than using conventional Nafion ionomer-based electrodes because of the hydrophilic nature and water retention characteristic of agar caused superior mass/charge transport in the fuel cell. Sun and Li proposed a concept of preparing anion-ionomer-free electrodes for anion-exchange membrane (QAPS membrane) DFFCs (AEM DFFCs) using Pd as the catalyst for both electrodes. The catalyst layers on both electrodes contained either QAPS (an anion-conducting material) or 10 wt% PTFE as a binder. The results showed that the AEM DFFC containing PTFE in the catalyst layers yielded higher peak power density than the other containing QAPS because the adhesion of PTFE on Pd/C results in a highly porous catalyst layer, and the hydroxide ion-containing formate solution facilitates mass and charge transport, thereby enlarging the triple-phase boundary for both anodic formate oxidation and cathodic oxygen reduction reactions. Pan et al compared the PVDF–HFP electrode binder with conventional Nafion and PTFE electrode binders in terms of the electrode morphology and performance of alkaline-acid direct ethylene glycol fuel cells possessing Nafion 211 membrane. They found that the fuel cell using the PVDF–HFP-based anode exhibited the highest peak power density because of the higher electrochemical surface area for its intrinsic porous property, followed by the fuel cell using Nafion-based electrode, and the worst was the fuel cell using PTFE-based electrode.

From the abovementioned literature, an ionomer is necessary for fabricating the DLFC anode, and both the ionomer type and content are important in fuel cell performance. Generally, for conducting anions, fuel cells having A3- and QAPS-based electrodes have been tested, whereas fuel cells having ACH- and Nafion-based electrodes have been tested for conducting cations. Furthermore, some neutral polymers such as PTFE and PVDF–HEP were also used as ionomers in the fuel cell electrode. Herein, alkaline, membraneless, DFFCs with an in-house fabricated anode are fabricated with a single serpentine channel as a fuel flow field over a large-scale electrode, compared to traditional MFCs. The anode and cathode catalyst layers will directly contact the HCOOK solution based on the finding of a previous study. Such design greatly simplifies the membraneless DFFC configuration with only one liquid stream needed for electricity generation. The effect of the contents of the easily accessible and cation-conducting Nafion ionomer on the performance of the anion-exchange, membraneless DFFCs will be tested and investigated.
2 | EXPERIMENT

2.1 | Fabrication of MFC

Herein, membraneless DFFCs with different amounts of Nafion ionomer added in the anode catalyst layer as a binder were tested at various concentrations and fuel flow rates at a 100-sccm airflow rate. Each MFC tested herein comprised two stainless steel plates as end plates of the fuel cells, PTFE gaskets to avoid leakage, gold-plated copper foils as electric collectors for both electrodes, composite carbon plate having a serpentine channel as airflow field plate, and a fuel/electrolyte flow field plate that was milled to achieve a through serpentine PEEK-made channel. The red and green arrows in the schematic of the membraneless DFFCs (Figure 1A), respectively, indicate the anolyte and airflow path from the inlet to the outlet. Note that the anode and cathode GDEs were placed on both sides of the fuel/electrolyte flow filed plate with the catalyst layer facing the fuel/electrolyte stream (Figure 1B). Several holes were drilled on the sidewalls of both end plates to install cartridge heaters and T-Type thermocouples, respectively, to maintain the fuel cells' temperature fixed at a specific value using a temperature control unit.

The thickness of the fuel/electrolyte and airflow field plates are 1.0 and 2.0 mm, respectively. The width, pitch, and depth of the serpentine microchannel fabricated on the airflow field plate are 0.8, 0.8, and 1.0 mm, respectively (Figure 2A), whereas the width and pitch of the through serpentine microchannel on the fuel/electrolyte flow field plate are both 0.8 mm (Figure 2B). Since the serpentine microchannel on the fuel/electrolyte flow field plate is through, the fuel/electrolyte flow could touch the catalyst layers on both electrodes. Figure 3A shows the arrangement of each component of the membraneless DFFCs, and the exterior dimensions of the actual membraneless DFFCs in Figure 3B are ~60 mm × 60 mm × 37 mm.

**FIGURE 1** Schematic of (A) membraneless DFFCs herein with reactant flow path indicated by red (fuel) and green (air) arrows, and (B) arrangement of GDEs and fuel flow field, and its working principle.
2.2 | Electrode preparation

The anode GDE was self-fabricated with different amounts of Nafion content. First, the Pd/C catalyst powder (30 wt%, Sigma-Aldrich 407 305) was ultrasonically dispersed in a solution containing deionized water, n-propyl alcohol, and an appropriate amount of Nafion® PFSA polymer dispersion (20 wt%, DE2020, DuPont™). The average diameter of Pd particles was 5.5 nm. Subsequently, the suspension was pipetted onto a carbon paper (Toray TGP-H-090). The carbon paper coated with catalyst slurry was finally dried in a vacuum oven at 80°C for 20 min to obtain the anode GDE with a fixed 2-mg/cm² Pd loading and desired amount of the Nafion content. Three different levels of the Nafion content in the anode catalyst layer were prepared and tested (Table 1). A commercially available GDE prepared using commercially available carbon-supported Pt catalyst (70 wt%, Alfa Aesar HiSPEC™13100) was employed as the cathode GDE. The resulting Pt loading on the cathode GDE was 2 mg/cm².

2.3 | Experimental setup

Figure 4 shows the experimental setup schematic comprising several major components, including a tested fuel cell, a fluid delivery system, an air-pumping system, an electronic load for cell performance measurement, and a cell temperature control unit. During the experiments, both electric collectors of the fuel cells were connected to an electronic load (KIKUSUI PLZ-70UA) to measure the polarization curve at ambient pressure under stepwise potentiostatic control. The voltage and current resolution for this electronic load are 0.1 mV and 0.01 mA, respectively. All polarization curves herein were measured with a 50-mV potential step from 1.0 to 0 V. Each potential's duration was 15 seconds, and data were recorded once every 0.5 second using a personal computer. Afterward, the mean of all values recorded at each potential was calculated. The current density \( i \) and power density \( p \) of this MFC are estimated based on the measured cell current \( J \), cell voltage \( V \), and effective electrode area \( A = 4.0 \text{ cm}^2 \) as follows.

\[
i = \frac{J}{A}
\]

\[
p = V \cdot i
\]

A peristaltic pump and its accessories (YOTEC PF103 and FL15) were employed to achieve the circulation between the fuel/electrolyte mixture solution tank and the tested fuel cell connected with silicone tubing at desired volumetric flow rates. Besides, to feed the fuel cells' cathode with atmospheric air, an air-pumping system comprising an air compressor (LIDA JW-1510N), a filter to prevent submicron particle and lubricant mist from entering the gas diffusion layer of the cathode, a pressure regulator to maintain a favorable air pressure before entering the flow meter, and a flow meter (NEW-FLOW TLFC-09-A-1-W-2-A-1-1) to control the flow rate into the cathode, was also used. The temperature control unit comprising a power supply, heaters, temperature sensors, and PID controllers was also employed to maintain a given temperature for the fuel cell and fuel/electrolyte mixture. A mixture of potassium formate (HCOOK) and potassium hydroxide (KOH) solutions was used as the fuel and supporting electrolyte while testing the fuel cells. Table 1 presents the HCOOK-to-KOH
molar ratio in the liquid stream. Millipore water (18.3 MΩ-cm, Millipore Milli-Q) was used to prepare the solution and clean the piping after the experiment. The membraneless DFFCs having three different Nafion ionomer contents in the catalyst layer in the fuel cell anode were tested at various concentrations and

**TABLE 1** Experimental condition herein

| Electrode conditions | Catalyst loading | Anode (Pd) | 2.0 mg/cm² |
|----------------------|------------------|------------|------------|
| Nafion ionomer content in anode | 1.87, 2.49, and 3.73 mg/cm² or 21.91 wt%, 27.19 wt%, and 35.88 wt% |

| Air and fuel flow field | Single serpentine with depth and width of 1.0 mm and 0.8 mm, respectively |
|-------------------------|------------------------------------------------------------------------|
| Electrode area          | 4.0 cm²                                                                |
| Tightening torque       | 3 N·m                                                                  |
| Operating conditions    | Room temperature, 30, 40, 50, and 60 |
| Volumetric flow rate    | Fuel: 1.0, 2.0, and 3.0 mL/min                                          |
| Air: 100 sccm           |                                                                         |
| Anolyte                | HCOOK as fuel and KOH as supporting electrolyte                       |
| Oxidant                | Air                                                                     |
| Anolyte composition    | 1/1 (F1/E1)                                                            |
| HCOOK/KOH (M)           | 1/3 (F1/E3)                                                            |
|                         | 1/5 (F1/E5)                                                            |
|                         | 3/1 (F3/E1)                                                            |
|                         | 3/3 (F3/E3)                                                            |
|                         | 3/5 (F3/E5)                                                            |
|                         | 5/1 (F5/E1)                                                            |
|                         | 5/3 (F5/E3)                                                            |
|                         | 5/5 (F5/E5)                                                            |
volumetric flow rates at different temperatures. Table 1 summarizes the experimental conditions.

3 | RESULTS AND DISCUSSION

The oxidation and reduction half-reaction of potassium formate and oxygen in alkaline media have been reported as follows:

\[
\text{HCOO}^- + 3\text{OH}^- \to \text{CO}_3^{2-} + 2\text{H}_2\text{O} + 2e^- E^0_a = -1.05 \text{ V} \quad (3)
\]

\[
\frac{1}{2}\text{O}_2 + \text{H}_2\text{O} + 2e^- \to 2\text{OH}^- E^0_c = 0.4\text{ V} \quad (4)
\]

Combining the aforementioned equations, the overall reaction of the alkaline DFFC can be expressed as,

\[
\text{HCOO}^- + \frac{1}{2}\text{O}_2 + \text{OH}^- \to \text{CO}_3^{2-} + \text{H}_2\text{O} \quad E^0_{\text{cell}} = 1.45\text{ V} \quad (5)
\]

Evidently, the theoretical open circuit voltage, which will later be denoted as OCV, shown above, is higher than that of hydrogen and direct methanol fuel cells.

Figure 5 shows the membraneless DFFC performance measured using 1-M formate mixed with KOH of various concentrations at various volumetric flow rates, as the Nafion ionomer content in the anode was 3.73 mg/cm².
The fuel cell performance increases as the fuel volumetric flow rate increases regardless of the KOH concentration. Besides, the KOH concentration increment at a given formate concentration can improve the fuel cell performance by reducing the cell internal resistance at the expense of the polarization curve retraction in the high current region of the $V-I$ curves. Since the KOH added in the HCOOK solution of the membraneless DFFCs is served as the liquid electrolyte that helps the hydroxide ions to conduct through the anolyte solution to the anode (Figure 1B), and the ionic conductivity of the anolyte solution usually increases as the liquid electrolyte concentration increases, the cell internal resistance could be reduced as the KOH concentration increases. The maximum power density in Figure 5 reaches 27.79, 38.74, and 38.17 mW/cm$^2$ with KOH concentrations of 1, 3, and 5 M, respectively, at a 3-mL/min volumetric flow rate. The polarization curve retraction in the high current region likely results from the cathode flooding, since no polymer membrane was used to separate the cathode from the anolyte solution. Besides, Zeng et al$^{15}$ found that the concentration overpotential in the high current region of the polarization curve of the DFFCs fed with 1-M HCOOK increases as the KOH concentration increases from 0.5 to 2.0 M in the anolyte solution because of the competitive adsorption between HCOOK and KOH on the Pd catalyst surface. The cathode flooding and the competitive adsorption between HCOOK and KOH might be responsible for the polarization curve retraction in the high current region.

Since the performance of this membraneless DFFCs always peaks at a 3.0-mL/min volumetric flow rate, irrespective of the anolyte composition, the results measured at the 3.0-mL/min flow rate will be discussed. Figure 6 plots the polarization curves measured at various HCOOK concentrations. The OCV decreases as the HCOOK concentration increases because of the cathode mixed potential, and such a drop is significant at low KOH concentration. Also, the membraneless DFFC tested with the anolyte solution containing 1-M KOH revealed relatively high ohmic overpotential, as mentioned earlier. The highest maximum power density in Figure 6 was ~54 mW/cm$^2$ when feeding the membraneless DFFC with the anolyte containing 3-M formate and 5-M KOH.

As the Nafion ionomer content in the anode decreases, the maximum power density and OCV increase at a given concentration (Figure 7A and B). In contrast to the results shown in Figure 6, the membraneless DFFC tested with 3-M HCOOK in 3-M KOH yielded the highest maximum power density in both Figure 7A and B. Figure 8 presents the graph showing the OCV value for the membraneless DFFC fed with 3-M HCOOK in 3-M KOH and 5-M HCOOK in 1-M KOH at various flow rates. It can be observed that the OCV is particularly low, 0.62-0.82 V, as the HCOOK concentration is much higher than the KOH concentration. However, it can increase to 0.92 V when HCOOK and KOH are of comparable concentrations, slightly depending on the Nafion ionomer content and flow rate. In fact, the OCV of this DFFC fed with the anolyte containing 5-M HCOOK in 5-M KOH is approximately 0.9 V or above depending on the testing condition.

Since the membraneless DFFCs fed with either the anolyte containing 3-M HCOOK in 3-M or 5-M KOH yielded

![Figure 6](image-url)
the highest power density, the maximum power density of the membraneless DFFC measured at both anolyte compositions at different Nafion ionomer contents is plotted in Figure 9. The maximum power density is increased monotonously as the flow rate increases. Besides, the lower the Nafion ionomer content in the anode, the higher the maximum power density herein. The curves in Figures 6 and 7 show that the maximum power density of the membraneless DFFC tested with the anolyte composition, other than those discussed in Figure 9, is significantly lower. The highest maximum power density reached approximately 66 mW/cm², as the anode of the membraneless DFFC contained 1.87-mg/cm² Nafion ionomer.

To discuss the effect of the Nafion ionomer content in the anode catalyst layer on the fuel cell performance, SEM images of the anodic electrode containing different Nafion ionomer contents are presented in Figure 10. Instead of showing the electrode’s clear carbon fibers in Figure 10A,
The rest of the SEM images in Figure 10 show numerous flakes of different sizes. It seems that the more the Nafion ionomer is added as a binder, the more the Pd/C powder agglomerates. After drying in the vacuum oven, the Pd/C powder agglomeration on the anode surface is likely to become structurally flaky (Figure 10B-D). However, the white, fluffy structures on the flakes, like the site where a pink arrow indicates in each SEM image, could be the highly porous catalyst sites because they look like the well-dispersed Pd/C powder, but not solid agglomerates. By observing Figure 10B and C, it seems that the fluffy structure on the anode surface can be uniformly spread as the Nafion ionomer content is few. This trend could explain why less Nafion ionomer content in the anode catalyst layer leads to higher OCV and maximum power density of the membraneless DFFC herein.

Since the highest cell output for the membraneless DFFC herein occurred when the membraneless DFFC having Nafion ionomer content of 1.87 mg/cm² in the anode with the anolyte solution containing 3-M HCOOK in 3-M KOH at a flow rate of 3 mL/min was fed, the polarization curves of the membraneless DFFC tested under the above-mentioned conditions at a specific temperature ranging from 30°C to 60°C are shown in Figure 11. As expected, the maximum power density of the membraneless DFFC increases as the cell temperature increases. The highest power density of the membraneless DFFC reached 81 and 85.6 mW/cm² at 50°C and 60°C, respectively. However, as the cell temperature increased from 50°C to 60°C, the gas bubble was exhausted from the liquid outlet during the experiment because the forced air invades the liquid passage for the incomparable thermal expansion of each fuel cell component. Furthermore, the aforementioned gas bubbles might also be CO₂, which has been reported as a possible side-product during the formate oxidation reaction in alkaline media. Based on the discussion in, it can be realized that CO₂ bubbles can be formed once the current produced is high enough. Therefore, the membraneless DFFC test is limited to 60°C herein.

Finally, Figure 12 compares the membraneless DFFC performance, herein, with that of the MFCs published in the literature under similar conditions. The detailed conditions under that the fuel cells were measured are listed below. First, the OCV value of this membraneless DFFC exceeds that of most fuel cells, except those tested by Pramanik and Rathoure and Liu et al in Figure 12. This trend occurs because the theoretical OCVs of the fuel cells in both studies are as high as 1.64 and 2.826 V, respectively, for the particular reactants used. However, the actual OCVs of most MFCs in Figure 12 are much lower than the theoretical OCVs, indicating a severe crossover effect and high mixed potential of such MFCs. To alleviate the crossover effect, Liu et al designed a particular fuel cell architecture by introducing an additional electrolyte stream between the fuel and oxidant, possibly leading to a notable ohmic overpotential and a steep polarization curve (Figure 12). The low mixed potential of the membraneless DFFC with its cathodic catalyst in contact with the fuel is responsible for its high OCV. Furthermore, since the fuel crossover does not significantly affect the performance of this membraneless DFFC, the performance of the membraneless DFFC could be further enhanced by fabricating the fuel flow field plate in Figure 2B to be extremely thin, and widening the channel in the fuel flow field to acquire larger active electrode area.

Second, the polarization curve of the present fuel cell seems to drop more rapidly than the curve measured by Yu,

FIGURE 8 OCV of DFFCs vs. anolyte flow rate at anolyte compositions of 3-M HCOOK in 3-M KOH, and 5-M HCOOK in 1-M KOH, at various anode Nafion ionomer contents

FIGURE 9 Maximum power density of DFFCs vs. anolyte flow rate at anolyte compositions of 3-M HCOOK in 3-M KOH, and 3-M HCOOK in 5-M KOH, at various anode Nafion ionomer contents
and Manthiram as the current density exceeds 200 mA/cm², because air was employed as the oxidant in this study instead of oxygen.

4 | CONCLUSION

Herein, alkaline, membraneless DFFCs possessing a particular electrode arrangement were proposed and fabricated, and the resulting alkaline, membraneless DFFCs were tested with varying Nafion ionomer contents ranging from 1.87 to 3.73 mg/cm² in the anode at various fuel flow rates, anolyte concentrations, and temperatures at a given airflow rate, 100 sccm. The catalyst in the anode and cathode are Pd and Pt, respectively, with 2-mg/cm² identical loading. The results are summarized below.

1. As the Nafion ionomer content decreases from 3.73 to 1.87 mg/cm² in the anode, the maximum power

**FIGURE 10** SEM images of anode with various Nafion ionomer content: (A) plain, (B) 1.87 mg/cm², (C) 2.49 mg/cm², and (D) 3.73 mg/cm²

**FIGURE 11** Performance of DFFCs having 1.87-mg/cm² anode Nafion ionomer content tested with anolyte solution containing 3-M HCOOK in 3-M KOH at 3.0-mL/min flow rate at various cell temperatures ranging from 30°C to 60°C
2. The OCV of the DFFCs was particularly low as the HCOOK concentration was much higher than the KOH concentration. However, the OCV can be increased to 0.92 V when HCOOK and KOH are of comparable concentrations, slightly depending on the Nafion ionomer content and flow rate.

3. The DFFC performance increased as either the operating temperature or fuel volumetric flow rate increased. However, gas bubbles are exhausted through the fuel outlet while testing the DFFCs at 60°C. The highest peak power density of the membraneless DFFCs reached 66.25 and 85.6 mW/cm² at room temperature and 60°C, respectively, when feeding the DFFCs containing anode Nafion ionomer of 1.87 mg/cm² with 3-M HCOOK in 3-M KOH at a flow rate of 3 mL/min.

4. Even with the arrangement of sandwiching anolyte stream between the anode and cathode catalyst layer, it was found that the mixed potential of this DFFC is insignificant compared to that of published MFCs utilizing aqueous fuel other than HCOOK. It is expected that the performance of the membraneless DFFC could be further enhanced by designing the fuel flow field plate to be extremely thin to reduce the internal resistance, as reported in, and widening the channel in the fuel flow field to make the electrode more useful with oxygen fed as the oxidant.
ACKNOWLEDGMENTS
The authors are indebted to Ministry of Science and Technology of Taiwan for the funding under the contract of MOST 108-2628-E-992-001-MY3.

ORCID
Jin-Cherng Shyu https://orcid.org/0000-0003-2580-1384

REFERENCES
1. Ong BC, Kamarudin SK, Basri S. Direct liquid fuel cells: a review. Int J Hydrogen Energy. 2017;42:10142-10157.
2. Jayashree RS, Yoon SK, Brushett FR, et al. On the performance of membraneless laminar flow-based fuel cells. J Power Sources. 2010;195:3569-3578.
3. Ahmed DH, Park HB, Lee KH, Sung HJ. The geometrical design of membraneless micro fuel cells: Failure and success. Int J Energy Res. 2010;34:878-896.
4. Shyu J, Huang C. Characterization of bubble formation in microfluidic fuel cells employing hydrogen peroxide. J Power Sources. 2011;196:3233-3238.
5. Shaegh SAM, Nguyen NT, Chan SH, Zhou W. Air-breathing membraneless laminar flow-based fuel cell with flow-through anode. Int J Hydrogen Energy. 2012;37:3466-3476.
6. Thorson MR, Brushett FR, Timberg CJ, Kenis PJA. Design rules for electrode arrangement in an air-breathing alkaline direct methanol laminar flow fuel cell. J Power Sources. 2012;218:28-33.
7. Lam A, Dara MS, Wilkinson DP, Fatih K. Aerobic and anaerobic operation of an active membraneless direct methanol fuel cell. Electrochim Commun. 2012;17:22-25.
8. Gowdhamamoorthi M, Arun A, Kiruthika S, Muthukumaran B. Perborate as novel fuel for enhanced performance of membraneless fuel cells. Ionics. 2014;20:1723-1728.
9. Shyu J, Wang P, Lee C, et al. Fabrication and test of an air-breathing microfluidic fuel cell. Energies. 2015;8:2082-2096. doi:10.3390/en8033282
10. Wang Q, Chen F, Liu Y, et al. AgSn intermetallics as highly selective and active oxygen reduction electrocatalysts in membraneless alkaline fuel cells. J Power Sources. 2018;404:106-117.
11. Pramanik H, Rathoure AK. Electrooxidation study of NaBH4 in a membraneless microfluidic fuel cell with air breathing cathode for portable power application. Int J Hydrogen Energy. 2017;42:5340-5350.
12. Liu Z, Ye D, Chen R, Zhang B, Zhu X, Liao Q. A dual-functional three-dimensional herringbone-like electrode for a membraneless microfluidic fuel cell. J Power Sources. 2019;438:227058.
13. Shyu J, Hung S. Flow field effect on the performance of direct formic acid membraneless fuel cells: a numerical study. Processes. 2021;9(5):746. https://doi.org/10.3390/pr9050746
14. Bartrom AM, Haan JL. The direct formate fuel cell with an alkaline anion exchange membrane. J Power Sources. 2012;214:68-74.
15. Zeng L, Tang ZK, Zhao TS. A high-performance alkaline exchange membrane direct formate fuel cell. Appl Energy. 2014;115:405-410.
16. da Silva SG, Silva JCM, Buzzo GS, Spinacé EV, Neto AO, Assumpção MHMT. PdAu/C electrocatalysts as anodes for direct formate fuel cell. Electrocatalysis. 2015;6:442-446.
17. Zhang B, Ye DD, Li J, Zhu X, Liao Q. Air-breathing microfluidic fuel cells with a cylinder anode operating in acidic and alkaline media. Electrocim Acta. 2015;177:264-269.
18. Yu X, Manthiram A. Catalyst-selective, scalable membraneless alkaline direct formate fuel cells. Appl Catal B-Environ. 2015;165:63-67.
19. Su X, Pan Z, An L. Performance characteristics of a passive direct formate fuel cell. Int J Energy Res. 2019;43:7433-7443.
20. An L, Chen R. Direct formate fuel cells: a review. J Power Sources. 2016;320:127-139.
21. Yu X, Cheng L, Liu Y, Manthiram A. A Membraneless Direct Isopropanol Fuel Cell (DIPAFC) Operated with a Catalyst-Selective Principle. J Phys Chem C. 2018;122:13558-13563.
22. Yu X, Manthiram A. Scalable membraneless direct liquid fuel cells based on a catalyst-selective strategy. Energy Environ Mater. 2018;1:13-19.
23. Li YS, Zhao TS, Liang ZX. Effect of polymer binders in anode catalyst layer on performance of alkaline direct ethanol fuel cells. J Power Sources. 2009;190:223-229.
24. Kang Y, Ren M, Yuan T, Qiao Y, Zou Z, Yang H. Effect of Nafion aggregation in the anode catalytic layer on the performance of a direct formic acid fuel cell. J Power Sources. 2010;195:2649-2652.
25. An L, Zhao TS, Zeng L. Agar chemical hydrogel electrode binder for fuel-electrolyte-fed fuel cells. Appl Energy. 2013;109:67-71.
26. Sun X, Li Y. Understanding mass and charge transports to create anion-ionomer-free high-performance alkaline direct formate fuel cells. Int J Hydrogen Energy. 2015;40:2649-2652.
27. Pan Z, Bi Y, An L. A cost-effective and chemically stable electrode binder for alkaline-direct ethylene glycol fuel cells. Appl Energy. 2020;258:114060.
28. Shyu J, Wei C, Lee C, Wang C. Investigation of bubble effect in microfluidic fuel cells by a simplified microfluidic reactor. Appl Therm Eng. 2010;30:1863-1871.

How to cite this article: Shyu J-C, Wang Y-L. Effects of Nafion ionomer content on the performance of membraneless direct formate fuel cells. Energy Sci Eng. 2021;9:2139–2150. https://doi.org/10.1002/ese3.971