Comparative performance evaluation of self-basifying direct formate fuel cells

Xianda Sun^a, Yinshi Li^{a,b,*}, Liang An^{c,*} Xiaomeng Lv^d

 ^aKey Laboratory of Thermo-Fluid Science and Engineering of MOE, School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi 710049, China
^bXi'an Jiaotong University Shenzhen Research School, Shenzhen, Guangdong, 518057, China
^cDepartment of Mechanical Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong SAR, China
^dDepartment of Missile Engineering, Rocket Force University of Engineering, Xi'an 710025, China

Abstract: Formate that is capable of synthesizing from electrochemical conversion of CO₂ efficiently is emerging as one of promising fuels for direct liquid fuel cells. In this work, a comparative study on performance of self-basifying direct formate fuel cell that contains non-platinum catalysts, neutral polymer and anion-exchange membrane is reported. Experimental result shows that the peak power density (PPD) of self-basifying direct formate fuel cell reaches 47 mW cm⁻² at 60 ^oC without additional base. It is found that the competition between the quickened electrokinetics and increased mass and charge transport resistances induces an optimal anode and cathode Pd loading of 3.0 mg cm⁻². The PPD first improves and then decreases with PTFE content in cathode, resulting in an optimal content of 10 wt%. In contrast, it decreases monotonically with anode PTFE content. In addition, the cell performance varies slightly with formate concentration due to the competitive adsorption between HCOO⁻ and OH⁻. A moderate oxygen flow rate of 100 sccm is required for the highest performance. Moreover, elevating operating temperature quickens electrokinetics and facilitates mass and charge transfer, improving cell performance significantly.

^{*}Corresponding author.

Mail: ysli@mail.xjtu.edu.cn, liang.an@polyu.edu.hk

Keywords: Fuel cell; direct formate fuel cell; self-basifying; electrokinetics; mass and

charge transfer

Converting CO₂ that is powered by solar and wind into storable chemicals, such as alcohol and formate, is a promising way to relieve global warming [1-5]. When using the as-prepared chemicals, direct liquid fuel cell (DLFC) that directly generates electricity from chemical energy stored in liquid fuel is regarded as an ideal utilization mode [6-11]. Particularly, DLFCs with anion-exchange membrane (AEM) possess great potential in portable and mobile applications owing to their striking advantages in comparison to hydrogen-based fuel cells: i) high energy density, ii) easy fuel storage, transport and handling, and iii) simple system structure. More importantly, alkaline environment not only accelerates electrokinetics of both anode and cathode electrode reactions, making the use of non-precious mental and non-metal catalysts possible, but also mitigates the corrosion of electrode materials [12-17].

As a solar fuel, formate has attracted extensive attention because: 1) As a carbonneutral and renewable fuel, formate is capable of producing from the electrochemical conversion of CO₂ at high faradaic efficiency [18-19], 2) formate possesses the characteristics of non-flammable, low toxicity and low cost, and it is safe and environmental-friendly to be commercially applied as food additives and deicing agents [20], 3) formate is stable for long time transportation and storage, and it can be readily handled in its liquid and solid state, 4) formate oxidation reaction (FOR) can be catalyzed easily in the alkaline environment, especially on palladium-based catalyst without CO poison formation on palladium surface [21-22], and 5) the thermodynamic voltage of alkaline direct formate fuel cell (DFFC) reaches 1.45 V, higher than other alkaline DLFCs fed with methanol and ethanol [23-24].

Owing to the inherent advantages, great efforts have been devoted to alkaline DFFCs and considerable progress has been made [25-36]. For example, when pumping 6.0 M HCOOK and 2.0 M KOH to anode, the polybenzimidazole-based DFFC produces a peak power density (PPD) up to 160 mW cm⁻² at 120 °C [25]. When lowering the operating temperature to 60 °C, an anion-exchange membrane-based DFFC supplied with 1.0 M HCOOK containing 2.0 M KOH yields a PPD of 144 mW cm⁻² [26], demonstrating the prospect of utilizing formate as fuel in DLFCs. After optimizing the anode fabrication method, the PPD of alkaline DFFC achieves 267 mW cm⁻², which is comparable to that of alkaline DLFC consuming alcohol fuels [27]. After that, a direct formate-peroxide fuel cell (DFPFC) was developed to further improve the cell performance. A PPD of 591 mW cm⁻² was achieved at 60 ^oC when providing 1.0 M HCOONa with 3.0 M NaOH to anode [33]. It should be noted that the additional base (typically NaOH or KOH) mixed in fuel solution indeed boosts cell performance, it however directly lowers system energy density [37-39]. In this regard, more recently, we proposed a hydroxide self-feeding anion-ionomer-free AEM DFFC, which produces a 40% higher peak powder density than the conventional anion-ionomer AEM DFFC [36]. Although appealing, the investigation in self-basifying direct formate fuel cells is far less understood. To this end, herein, a comparative performance evaluation of selfbasifying direct formate fuel cell is reported. Special efforts are devoted to the effects of electrode compositions and operating conditions on the cell performance. It demonstrates that the optimized self-basifying DFFC produces a PPD up to 47 mW cm⁻ ² without both the additional base and anion ionomer.

Experimental

Membrane electrode assembly (MEA) Preparation. –The MEA (1.0 cm \times 1.0 cm) was made up of anode, quaternary ammonia polysulfone (QAPS) AEM and cathode. QAPS ionomer solution was used to cast the AEM [40]. Palladium chloride aqueous solution was reduced by sodium borohydride to obtain Pd/C nanoparticles [41]. The diffusion layer of both anode and cathode electrodes was composed of a carbon paper and a micro-porous layer (MPL), which contained 4.0 mg cm⁻² C and 40 wt% PTFE. The as-synthesized Pd/C nanoparticles were mixed with PTFE neutral polymer and ethanol to form catalyst inks. After stirred for 15 min in an ultrasonic bath, the catalyst inks were directly brushed on the MPL to form anode and cathode electrodes.

Fuel cell setup and measurement instrumentation.–The cell performance measurements were carried out by Arbin BT-G. The MEA was fixed between a pair of current collectors, which contain single serpentine flow field. The formate solution (1.0 mL min⁻¹) was pumped to the anode. The oxygen (99.5%) without humidification at ambient pressure was supplied into the cathode by a mass flow controller. Two heating rods were installed in the current collectors to control operating temperature. DC pulse method was used to measure cell resistance.

Results and discussion

Effect of anode Pd loading.–The polarization and power density curves of selfbasifying direct formate fuel cell with different anode Pd loadings ranging from 1.0 to 4.0 mg cm⁻² were shown in Fig.1. As seen, the cell performance is improved significantly with Pd loading from 1.0 to 3.0 mg cm⁻². The PPD is 26 mW cm⁻² at Pd loading of 1.0 mg cm⁻², and it rises to 37 mW cm⁻² when Pd loading is increased to 3.0 mg cm⁻². The limiting current density (LCD) also increases from 95 to 130 mA cm⁻². The improvement of cell performance can be mainly attributed to the increased catalytic active sites, resulting in the extended triple-phase boundary (TPB) for FOR. However, the cell performance decreases dramatically with high Pd loading of 4.0 mg cm⁻². The PPD and LCD decrease to 27 mW cm⁻² and 120 mA cm⁻², respectively. This is the outcome of thickening anode catalyst layer (CL). Theoretically, the molar flux of reactants in the anode CL (N_i) can be written based on Fick's law:

$$N_{i} = -D_{i}^{\text{eff}} \frac{dc_{i}}{d\delta} = D_{i}^{\text{eff}} \frac{c_{i}^{\text{mpl/cl}} - c_{i}^{\text{Pd,surf}}}{\delta}$$
(1)

where *i* represents HCOO⁻ or OH⁻, D_i^{eff} is the effective diffusion coefficient of reactant in anode CL, c_i denotes the concentration of reactant, $c_i^{\text{mpl/cl}}$ is the reactant concentration at the interface between anode MPL and CL, $c_i^{\text{Pd,surf}}$ represents the reactant concentration on the Pd surface, δ is the transport length from the MPL/CL interface to Pd surface. The species transport resistance in the anode CL (R_T^{cl}) can be defined as follows:

$$R_{\rm T}^{\rm cl} = \frac{\Delta c}{N_{\rm i}} = \frac{c_{\rm i}^{\rm mpl/cl} - c_{\rm i}^{\rm Pd, surf}}{N_{\rm i}}$$
(2)

where Δc represents the change in reactant concentration from the anode MPL/CL interface to the Pd surface. Combining equations (1) and (2), R_T^{cl} can be further expressed as:

$$R_{\rm T}^{\rm cl} = \frac{\delta}{D_{\rm i}^{\rm eff}} \tag{3}$$

thereby, on one hand, the thick anode CL impedes the transport of both hydroxide ion

and electron, thus increasing the charge transport resistance, which can be confirmed by that the cell resistance increases from 304 to 398 m Ω (see Fig. 1b). On the other hand, the thick anode CL blocks the mass transport, thereby increasing the concentration loss, resulting in poor cell performance. In summary, a tradeoff between electrokinetics and species transport resistance leads to the maximum peak power density for self-basifying DFFC at anode Pd loading of 3.0 mg cm⁻².

Effect of anode PTFE content.–The performance characteristics of self-basifying DFFC with different anode PTFE contents were investigated. As shown in Fig. 2a, the PPD drops from 41 to 22 mW cm⁻² with anode PTFE content varying from 5 to 30 wt%. The PPD decreases monotonically with anode PTFE content is explained as follows. The agglomerate is formed in anode CL because the PTFE binder adheres Pd/C nanoparticles, so as to cover the active sites, decreasing the electrochemical surface area (ECSA). As a result, the anode FOR is decelerated, as evidenced by the dropped open cell voltage (OCV) from 829 to 783 mV (see Fig. 2b). Additionally, the number of agglomerates increases with the PTFE content. In this regard, too many agglomerates not only diminish the ECSA but also hinder the transport of hydroxide ion, electron and reactant, aggravating the activation, ohmic and concentration losses. The increased charge transport resistance can be confirmed by the cell resistance that rises from 310 to 428 mΩ with anode PTFE content as demonstrated in Fig. 2c.

Effect of cathode Pd loading.–The cell performance curves for the effect of cathode Pd loading are presented in Fig. 3a. As observed, when increasing Pd loading from 1.0 to 4.0 mg cm⁻², the cell voltage of self-basifying DFFC improves

monotonically at low current density regions. This phenomenon can be ascribed to that more catalytic active sites are provided by the increased Pd loading to enlarge ECSA, which quickens oxygen oxidation reaction (ORR), thus increasing the cell voltage. However, at high current density regions, the PPD of the self-basifying DFFC first improves and then decreases with cathode Pd loading. This is because the increased Pd loading speeds up the ORR, lowering the activation loss. While, the thick cathode CL: i) prolongs hydroxide ion transfer, causing a high ohmic loss as evidenced from the increased cell resistance from 310 to 384 m Ω (see Fig. 3b), and ii) hinders the oxygen transport, raising the concentration loss, which can be confirmed by the reduced LCD from 170 to 130 mA cm⁻² (see Fig. 3a). Therefore, the highest PPD of 47 mW cm⁻² appears at cathode Pd loading of 3.0 mg cm⁻².

Effect of cathode PTFE content.–The performance characteristics of selfbasifying DFFC with different cathode PTFE contents were shown in Fig. 4a. It can be seen the cell voltage decreases with cathode PTFE content at low current density regions. However, it first increases and then decreases at high current density regions. The reasons are explained as follows. Let us first look at the water and oxygen transport that is primarily driven by the capillary pressure p_c [42-43]:

$$p_{\rm c} = 2\sigma \, \frac{\cos(\theta_{\rm c})}{r_{\rm c}} \tag{4}$$

where σ is the interfacial tension, θ_c represents the contact angle and r_c is the pore radius. When increasing PTFE content, the hydrophobicity of cathode CL increases while the pore radius reduces. As a result, a high capillary pressure appears, enhancing water removal and oxygen transport, leading to improving cell performance. However, the porosity of the cathode CL decreases with PTFE content, which in turn increases the oxygen transport resistance, lowering cell performance. Moreover, when varying PTFE content from 5 to 30 wt%, many active sites are covered or isolated by the PTFE natural polymer, reducing the triple-phase boundary, thereby slowing down the electrokinetics of ORR, which can be verified by the diminished OCV from 851 to 826 mV (see Fig. 4b). Meanwhile, the incorporation of PTFE into the cathode CL blocks the transfer of both hydroxide ion and electron, increasing the ohmic loss as evidenced by the increased cell resistance from 322 to 611 m Ω . Hence, the optimal cathode PTFE (10 wt%) is obtained for self-basifying DFFC.

Effect of oxygen flow rate and formate concentration.–As shown in Fig. 5a, both the PPD and LCD increases with O₂ flow rate from 5 to 100 sccm. The improved performance is owing to the fact that the increased O₂ flow rate not only promises an effective O₂ supplement to the active sites but also enhances the water removal in cathode CL, thus improving cell performance. However, the cell performance decreases with further increasing O₂ flow rate to 150 sccm. The explanation for reduced cell performance is as below. On one hand, too high O₂ flow rate reduces the water uptake in membrane, lowering the ion conductivity, which can be confirmed by the increased cell resistance from 304 to 355 mΩ (see Fig. 5b). On the other hand, it should be mentioned that water as a reactant reacts with oxygen to produce OH⁻ ions. Too high oxygen flow rate gives rise to the local starvation of water in the cathode CL, and thus lowering the cell performance. In contrast. Due to the competitive adsorption between HCOO⁻ and OH⁻ ions [26], the cell performance varies slightly with formate concentration as demonstrated in Fig. 6.

Effect of operating temperature.–Fig. 7a presents the performance curves of self-basifying DFFC at different operating temperatures. As seen, the PPD of 23 mW cm⁻² and the LCD of 85 mA cm⁻² are obtained at 25 °C. When increasing operating temperature to 60 °C, they increases to 47 mW cm⁻² and 150 mA cm⁻², respectively. Elevating operating temperature: i) quickens electrokinetics of both FOR and ORR, lowering the activation loss, which can be evidenced from the improved OCV (see Fig. 7b), ii) increases the conductivity of both hydroxide ion and electron, thereby reducing the ohmic loss, which can be confirmed by the decreased cell resistance (see Fig. 7c), and iii) enhances the mass transport, diminishing the concentration loss. In summary, raising operating temperature within a certain range can improve the cell performance remarkably.

Conclusions

To comparatively evaluate the performance of self-basifying direct formate fuel cells, in this work, the influences of electrode compositions and operating conditions were studied. Experimental result shows that the self-basifying DFFC eliminating both the additional base and anion ionomer produces a PPD up to 47 mW cm⁻². It was found that the cell performance first improves and then decreases with the catalyst loading of both anode and cathode. This phenomenon is ascribed to the balance between the positive effect of the extended TPB and the negative effect of the increased species transport resistance. The optimal Pd loading is 3.0 mg cm⁻² for both anode and cathode. This is

because increasing cathode PTFE content decreases the ECSA and increases the species transport resistance. While, it also facilitates the water removal in the cathode CL, which in turn enhances the oxygen transport. In contrast, the PPD decreases monotonically with anode PTFE content. The cell performance varies slightly with formate concentration due to the competitive adsorption between HCOO⁻ and OH⁻. An increase in oxygen flow rate not only enhances the oxygen transport but also affects the content of water as a reactant. Therefore, a moderate oxygen flow rate of 100 sccm is suitable for the highest performance. Elevating operating temperature quickens electrokinetics and facilitates mass and charge transfer, improving cell performance significantly.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (51776156), Shenzhen Science and Technology Foundation (JCYJ20170816100910119), and Natural Science Basic Research Plan in Shaanxi Province of China (2019JM-011).

References

- [1] K. Schuchmann and V. Muller, Science, 342, 1382 (2013).
- [2] S. Fukuzumi, Joule, 1, 689 (2017).
- [3] W. H. Wang, Y. Himeda, J. T. Muckerman, G. F. Manbeck and E. Fujita, *Chem. Rev.*, **115**, 12936 (2015).
- [4] S. Kar, A. Goeppert, V. Galvan, R. Chowdhury, J. Olah and G. K. S. Prakash, J. Am. Chem. Soc., 140, 16873 (2018).
- [5] R. Wang, Y. S. Li and Y. L. He, J. Mater. Chem. A, 7, 10962 (2019).
- [6] B. Y. Song, Y. He, Y. L. He, D. Huang and Y. W. Zhang, *Energy*, 176, 15 (2019).
- [7] H. R. Jiang, L. Wei, X. Z. Fan, J. B. Xu, W. Shyy and T. S. Zhao, *Sci. Bull.*, 64, 270 (2019).
- [8] E. Antolini and E. R. Gonzalezb, J. Power Sources, 195, 3431 (2010).
- [9] Y. S. Li and Y. L. He, J. Electrochem. Soc., 163, F663 (2016).
- [10] O. Muneeb, I. Chino, A. Saenz and J. L. Haan, J. Power Sources, 413, 216 (2019).
- [11] X. D. Sun, Y. S. Li and M. J. Li, ACS Sustain. Chem. Eng., 2019, DOI: org/10.1021/acssuschemeng.9b00355.
- [12] Z. P. Xiang, H. Q. Deng, P. Peljo, Z. Y. Fu, S. L. Wang, D. Mandler, G. Q. Sun and Z. X. Liang, Angew. Chem. Int. Ed., 57, 3464 (2018).
- [13] C. Wang, X. J. Cheng, X. H. Yan, S. Y. Shen, C. C. Ke, G. H. Wei, and J. L. Zhang, *J. Electrochem. Soc.*, **166**, F239 (2019).
- [14] G. F. Long, X. H. Li, K. Wan, Z. X. Liang, J. H. Piao and P. Tsiakaras, *Appl. Catal. B Environ.*, **203**, 541 (2017).
- [15] R. Wang and Y. S. Li, J. Power Sources, 421, 139 (2019).
- [16] T. Y. Cao, K. Huang, Y. X. Shi and N. S. Cai, J. Power Sources, 403, 76 (2018).

- [17] A. E. Kasmi, M. Waqas, P. M. Koutou and Z. Y. Tian, J. Therm. Sci., 28, 225 (2019).
- [18] W. Lee, Y. E. Kim, M. H. Youn, S. K. Jeong and K. T. Park, Angew. Chem. Int. Ed., 57, 6883 (2018).
- [19] T. Q. Nguyen, A. M. Bartrom, K. Tran and J. L. Haan, Fuel Cells, 13, 922 (2013).
- [20] T. Vo, K. Purohit, C. Nguyen, B. Biggs, S. Mayoral and J. L. Haan, *ChemSusChem*, 8, 3853 (2015).
- [21] T. Q. Nguyen, D. Minami, C. Hua, A. Miller, K. Tran and J. L. Haan, J. Fuel Cell Sci. Technol., 12, 1 (2015).
- [22] L. An and R. Chen, J. Power Sources, 320, 127 (2016).
- [23] X. W. Yu and A. Manthiram, Appl. Catal. B Environ., 165, 63 (2015).
- [24] L. Q. Wang, M. Bellini, J. Filippi, M. Folliero, A. Lavacchi, M. Innocenti, A. Marchionni, H. A. Miller and F. Vizza, *Appl. Energy*, **175**, 479 (2016).
- [25] J. H. Jiang and A. Wieckowski, *Electrochem. Commun.*, 18, 41 (2012).
- [26] A. M. Bartrom and J.L. Haan, J. Power Sources, 214, 68 (2012).
- [27] A. M. Bartrom, J. Ta, T. Q. Nguyen, J. Her, A. Donovan and J. L. Haan, J. Power Sources, 229, 234 (2013).
- [28] L. Zeng, Z. K. Tang and T.S. Zhao, Appl. Energy, 115, 405 (2014).
- [29] B. Yan, N. M. Concannon, J. D. Milshtein, F. R. Brushett and Y. Surendranath, Angew. Chem. Int. Ed., 56, 7496 (2017).
- [30] L. An and R. Chen, Appl. Therm. Eng., 124, 232 (2017).
- [31] Y. S. Li, Y. Feng, X. D. Sun and Y. L. He, Angew. Chem. Int. Ed., 56, 5734 (2017).
- [32] H. A. Miller, J. Ruggeri, A. Marchionni, M. Bellini, M. V. Pagliaro, C. Bartoli, A. Pucci, E. Passaglia and F. Vizza, *Energies*, **11**, 1 (2018).
- [33] Y. S. Li, H. Wu, Y. L. He, Y. Liu and L. Jin, J. Power Sources, 287, 75 (2015).

- [34] E. Kjeang, R. Michela, D. A. Harrington, D. Sinton and N. Djilali, *Electrochem. Acta*, 54, 698 (2008).
- [35] V. Galvan, K. Domalaon, C. Tang, S. Sotez, A. Mendez, M. J. Heravi, K. Purohit,L. Pham, J. L. Haan, and F. A. Gomez, *Electrophoresis*, 37, 504 (2016).
- [36] X. D. Sun and Y. S. Li, Int. J. Hydrogen Energy, 44, 7538 (2019).
- [37] Z. Y. Wang, J. Parrondo, C. He, S. Sankarasubramanian and V. Ramani, Nat. Energy, 4, 281 (2019).
- [38] Y. S. Li, J. Hydrogen Energy, 41, 3600 (2016).
- [39] E. H. Yu, X. Wang, U. Krewer, L. Lid and K. Scott, *Energy Environ. Sci.*, 5, 5668 (2012).
- [40] Y. S. Li, X. D. Sun and Y. Feng, ChemSusChem, 10, 2135 (2017).
- [41] S. Y. Shen, T. S. Zhao and J. B. Xu, J. Power Sources, 195, 1001 (2010).
- [42] G. Q. Lu, F. Q. Liu and C. Y. Wang, Electrochem. Solid-State Lett., 8, 1 (2005).
- [43] J. Zhao, S. Shahgaldi, A. Ozden, I. E. Alaefour, X. G. Li and F. Hamdullahpur, *Int. J. Energy Res.*, 42, 1 (2018).



Figure 1 Effects of anode Pd loading on (a) cell performance, and (b) cell resistance. Anode fuel: HCOOK (1.0 M, 1.0 mLmin⁻¹); Cathode oxidant: O₂ (100 sccm, ambient pressure); Anode catalyst: Pd/C (loading: 1.0, 2.0, 3.0, and 4.0 mg_{Pd} cm⁻²); Anode

binder: PTFE (content: 10 wt%); Cathode catalyst: Pd/C (loading: 1.0 mg_{Pd} cm⁻²); Cathode binder: PTFE (content: 10 wt%); AEM: QAPS membrane; operating temperature: 60 ^oC.







Figure 2 Effects of anode PTFE content on (a) cell performance, (b) open-circuit voltage, and (c) cell resistance. Anode fuel: HCOOK (1.0 M, 1.0 mLmin⁻¹); Cathode oxidant: O_2 (100 sccm, ambient pressure); Anode catalyst: Pd/C (loading: 3.0 mg_{Pd} cm⁻²); Anode binder: PTFE (content: 5 wt%, 10 wt%, 20 wt%, and 30 wt%); Cathode catalyst: Pd/C (loading: 1.0 mg_{Pd} cm⁻²); Cathode binder: PTFE (content: 10 wt%); AEM: QAPS membrane; operating temperature: 60 ^oC.



Figure 3 Effects of cathode Pd loading on (a) cell performance, and (b) cell resistance. Anode fuel: HCOOK (1.0 M, 1.0 mLmin⁻¹); Cathode oxidant: O_2 (100 sccm, ambient pressure); Anode catalyst: Pd/C (loading: 3.0 mg_{Pd} cm⁻²); Anode binder: PTFE (content:

5 wt%); Cathode catalyst: Pd/C (loading: 1.0, 2.0, 3.0, and 4.0 mg_{Pd} cm⁻²); Cathode binder: PTFE (content: 10 wt%); AEM: QAPS membrane; operating temperature: 60 0 C.







Figure 4 Effects of cathode PTFE content on (a) cell performance, (b) open-circuit voltage, and (c) cell resistance. Anode fuel: HCOOK (1.0 M, 1.0 mLmin⁻¹); Cathode oxidant: O_2 (100 sccm, ambient pressure); Anode catalyst: Pd/C (loading: 3.0 mg_{Pd} cm⁻²); Anode binder: PTFE (content: 5 wt%); Cathode catalyst: Pd/C (loading: 3.0 mg_{Pd} cm⁻²); Cathode binder: PTFE (content: 5 wt%, 10 wt%, 20 wt%, and 30 wt%); AEM: QAPS membrane; operating temperature: 60 ^oC.



Figure 5 Effects of oxygen flow rate on (a) cell performance, and (b) cell resistance. Anode fuel: HCOOK (1.0 M, 1.0 mLmin⁻¹); Cathode oxidant: O₂ (5 sccm, 50sccm, 100 sccm, and 150 sccm, ambient pressure); Anode catalyst: Pd/C (loading: 3.0 mg_{Pd} cm⁻²);

Anode binder: PTFE (content: 5 wt%); Cathode catalyst: Pd/C (loading: 3.0 mg_{Pd} cm⁻²); Cathode binder: PTFE (content: 10 wt%); AEM: QAPS membrane; operating temperature: 60 ⁰C.



Figure 6 Effects of formate concentration on cell performance. Anode fuel: HCOOK (0.5 M, 1.0 M, 1.5 M, and 2.0 M, 1.0 mLmin⁻¹); Cathode oxidant: O₂ (100 sccm, ambient pressure); Anode catalyst: Pd/C (loading: $3.0 \text{mg}_{Pd} \text{ cm}^{-2}$); Anode binder: PTFE (content: 5 wt%); Cathode catalyst: Pd/C (loading: $3.0 \text{ mg}_{Pd} \text{ cm}^{-2}$); Cathode binder: PTFE (content: 10 wt%); AEM: QAPS membrane; operating temperature: 60 ^oC.





Figure 7 Effects of operating temperature on (a) cell performance, (b) open-circuit voltage, and (c) cell resistance. Anode fuel: HCOOK (1.0 M, 1.0 mLmin⁻¹); Cathode oxidant: O_2 (100 sccm, ambient pressure); Anode catalyst: Pd/C (loading: 3.0 mg_{Pd} cm⁻²); Anode binder: PTFE (content: 5 wt%); Cathode catalyst: Pd/C (loading: 3.0 mg_{Pd} cm⁻²); Cathode binder: PTFE (content: 10 wt%); AEM: QAPS membrane; operating temperature: 20 °C, 40 °C and 60 °C.