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The Influence of Hydrogen Flow Rate and Humidifier Temperature on Performance of a PEMFC with Ti-Co/C Catalyst

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Abstract

This study explores the effect of hydrogen flow rate and humidifier temperature on the performance of the Membrane Electrode Assembly (MEA) using Ti-Co/C catalyst at the cathode and Pt/C at the anode in a single-cell Proton Exchange Membrane Fuel Cell (PEMFC). MEAs were fabricated by the spraying method and characterized using cyclic voltammetry (CV) and electrochemical impedance spectroscopy (EIS) to determine their electrochemical surface area (ECSA) and conductivity. The results showed that the optimized ECSA value reached 8.38 cm^2/g, and the electrical conductivity was 3.76×10^{-8} S/cm. The best performance was achieved at a hydrogen flow rate of 100 mL/min and room temperature humidification. Under the hydrogen flow rate test, the maximum power density reached 0.364 mW/cm^2, while in the humidifier temperature variation, a maximum power density of 0.375 mW/cm^2 was obtained at a current density 2.8 mA/cm^2. These findings suggest that Ti-Co/C is a promising low-cost catalyst alternative to Pt and that operational conditions play a critical role in MEA performance.

Keywords: Ti-Co/C catalyst, MEA, PEMFC, hydrogen flow rate, humidifier temperature

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Abstrak (Indonesian)

Penelitian ini bertujuan untuk mengevaluasi pengaruh laju alir gas hidrogen dan suhu humidifier terhadap kinerja Membrane Electrode Assembly (MEA) pada Proton Exchange Membrane Fuel Cell (PEMFC) sel tunggal. MEA disusun menggunakan elektroda katoda berbasis katalis Ti-Co/C dan anoda berbasis Pt/C, yang dibuat melalui metode penyemprotan. Karakterisasi dilakukan dengan menggunakan metode cyclic voltammetry (CV) untuk menentukan luas permukaan aktif elektrokimia (ECSA) dan electrochemical impedance spectroscopy (EIS) untuk mengukur konduktivitas listrik. Hasil menunjukkan bahwa nilai ECSA optimum mencapai 8,38 cm^2/g, sedangkan nilai konduktivitas listrik sebesar $3,76 \times 10^{-8}$ S/cm. Kinerja optimum MEA diperoleh pada laju alir hidrogen 100 mL/menit dan suhu humidifier pada suhu ruang. Pada uji kinerja pada laju alir hidrogen, didapatkan densitas daya maksimum sebesar 0,364 mW/cm^2, sementara itu uji kinerja pada suhu humidifier didapatkan densitas daya maksimum sebesar 0,735 mW/cm^2 pada densitas arus maksimum 2,8 mA/cm^2. Temuan ini mengindikasikan bahwa katalis Ti-Co/C berpotensi menjadi alternatif katalis rendah biaya pengganti Pt, serta menunjukkan bahwa kondisi operasi memiliki pengaruh signifikan terhadap performa MEA.

Kata Kunci: Katalis Ti-CO/C, MEA, PEMFC, laju alir hidrogen, suhu humidifier

INTRODUCTION

The global push for clean, sustainable energy technologies has elevated the importance of Proton Exchange Membrane Fuel Cells (PEMFCs) due to their excellent energy conversion efficiency, moderate operating temperature, and minimal environmental emissions. The single-stack PEMFC is composed of various components, including bipolar plates, gas diffusion layers (GDLs), catalyst layers, membranes, sealing gaskets, and other supporting elements [1]. A core part of PEMFC systems contributing directly to electrical power generation is the Membrane Electrode Assembly (MEA). The MEA is fabricated by combining electrodes composed of several layers, including carbon paper, a catalyst layer, and a polymer membrane. It serves as the site of electrochemical reactions and represents the core element that determines the performance level of the integrated PEMFC system [2], where the electrochemical reactions and thus overall efficiency occur. In particular, Ti-Co/C catalysts have shown promising electrochemical characteristics, including respectable electrochemical surface area (ECSA) and conductivity. A study by Adhiyanti *et al*. [3] reported an ECSA of 28.72 cm^2/g (carbon dots support), 2.34 cm^2/g (carbon Vulcan support), and a conductivity of 0.1688×10^{-3} S/cm for a Ti-Co/C (carbon dots support) catalyst layer. It is evidence of its suitability for PEMFC applications.

In addition to platinum (Pt), various other metals have been explored as potential catalysts for use in PEMFCs. Among them, titanium (Ti) offers several advantages over other metals, including superior corrosion resistance, high thermal stability, chemical inertness, and a relatively low atomic mass [4]. Moreover, when used as a catalyst material, titanium exhibits high stability in acidic media and demonstrates strong interactions with metal nanoparticles. These properties make titanium suitable for forming alloys with other metals such as aluminium, nickel, vanadium, and iron, and contribute to its stability and suitability for use in PEMFC applications [5]. The combination of platinum and cobalt catalysts has also been investigated in PEMFCs, demonstrating reversible catalytic activity. In this context, cobalt can be utilised either as a catalyst support [6]. Titanium enhances the dispersion of cobalt nanoparticles, improves corrosion resistance, and facilitates electron transport through strong metal–support interactions. Meanwhile, cobalt provides the main active sites for the oxygen reduction reaction (ORR) through reversible Co^{2+}/Co^{3+} redox transitions. The Ti–Co interface creates synergistic electronic interactions and oxygen vacancies that promote ORR kinetics and improve catalyst durability [7,8].

The key of operational parameters influencing MEA performance include catalyst composition, reactant gas flow rates, and humidification levels. Hydrogen flow rate and humidifier temperature play critical roles by ensuring adequate fuel distribution and membrane hydration while avoiding issues such as fuel crossover, membrane dehydration, and flooding. Optimising hydrogen flow is essential. Insufficient flow leads to fuel starvation and reduced current density, whereas excessive flow may result in hydrogen crossover, where unreacted fuel passes through the membrane without dissociation, leading to heat generation and diminished cell efficiency [9]. Seo (2025) provides recent empirical evidence that the hydrogen flow rate plays a critical role in PEMFC operation. Insufficient hydrogen flow can cause fuel depletion and crossover effects, whereas excessive flow may lead to flooding and hinder mass transport within the cell [10, 11]. The hydrogen supply must also be carefully regulated to avoid excessive delivery, which can reduce the membrane's optimal performance. An oversupply of hydrogen may pass through the membrane without undergoing dissociation into protons and electrons, leading to heat build-up within the PEMFC stack [12]. Meanwhile, humidifier temperature must maintain the membrane at an optimum hydration level. Inadequate humidity increases internal resistance, while over-humidification causes flooding that restricts gas transport [13].

MATERIALS AND METHODS

Materials

The Ti-Co/C catalyst used in this study was previously synthesized [3], Carbon Vulcan XC-72R (Fuel Cell Store), Nafion NR 212 solution (Fuel Cell Store), ammonium carbonate (Merck), 2-propanol (Sigma-Aldrich), PTFE emulsion DISP 30LX (Fuel Cell Store), and a backing layer in the form of carbon paper.

Preparation of cathode electrode using Ti-Co/C catalyst

A 0.03 g of Ti-Co/C catalyst, corresponding to a 0.5 mg/cm^2 loading, was dispersed in 1.37 mL of isopropanol and mixed with 0.028 g of Nafion solution. The mixture was homogenized using an ultrasonic homogenizer for 10 minutes. Subsequently, 0.01 g of PTFE was added, and the mixture was further homogenized for 5 minutes until a uniform Ti-Co/C

catalyst ink was formed. The resulting ink was loaded into a spray gun and uniformly sprayed onto a 5 × 5 cm gas diffusion layer (GDL) in alternating horizontal and vertical directions until the ink was used entirely. The fabricated electrode was dried in a furnace at 350 °C for 3 hours, resulting in a Ti-Co/C catalyst layer firmly attached to the GDL.

Preparation anode electrode using Pt/C catalyst

An amount of 0.11 g Pt/C catalyst, corresponding to a loading of 0.5 mg/cm², was moistened with deionized water and subsequently dispersed in 4.4 mL of isopropanol. Subsequently, 0.093 g of Nafion solution was added, and the mixture was homogenized using an ultrasonic homogenizer for 10 minutes. Afterwards, 0.03 g of PTFE was added, and the mixture was further stirred for 5 minutes until a homogeneous Pt/C catalyst ink was obtained. The catalyst ink was then loaded into a spray gun and uniformly sprayed onto a 5 × 5 cm^2 gas diffusion layer (GDL) in alternating horizontal and vertical directions until the ink was entirely consumed. The electrode was dried in a furnace (350 °C, 3 h), resulting in a Pt/C catalyst layer firmly adhered to the GDL.

MEA fabrication

The Membrane Electrode Assembly (MEA) was fabricated using two electrodes (an anode and a cathode) and a Nafion-212 electrolyte membrane, each with dimensions of 5 × 5 cm^2. The MEA was prepared by pressing the two electrodes onto both sides of the Nafion-212 membrane using a hot press. Before assembly, the electrodes were aligned and attached to each membrane side, then covered with aluminium foil to ensure uniform pressure distribution. The hot-pressing process was carried out at a temperature of 135 °C and a pressure of 2,000 psi for 3 minutes to ensure proper adhesion between the catalyst layers and the membrane.

Analysis Data

Electrode characterization

Cyclic voltammetry (CV) is one of the most commonly used methods to observe the results of redox reactions in electroactive materials. The response in the CV related to the scan rate is recorded through the cathodic and anodic currents on the voltammogram curve [14].

CV and Electrochemical Impedance Spectroscopy (EIS) measurements aim to characterize the electrochemical properties of electrodes. CV and EIS measurements were conducted using an Autolab PGSTAT 302N, and the data were analysed using NOVA software (version 1.8.14). The CV testing represents a half-cell reaction conducted using a 1 M NaOH electrolyte solution, an Ag/AgCl reference electrode, a Pt counter electrode, and Ti-Co/C electrode. All measurements were performed at a constant scan rate of 20-40 mV/s.

The presence of peaks in CV measurements is associated with chemisorption on the catalyst surface and the processes of mass transport [15]. The electrode conductivity is determined using the Equation (1)

$$\sigma = \frac{1}{Zr} \times \frac{1}{A} \quad (1)$$

σ represents conductivity (S/cm), Zr is the total electrical resistance (Rp + Rs) in ohms (Ω), l is the pallet thickness (cm), and A is the electrode contact surface area (cm^2) [15–17].

The electrochemical surface area (ECSA), used to assess the catalytic activity of the Ti-Co/C catalyst, was calculated according to Equation (2):

$$ECSA = \frac{QH}{(Qref \times Cloading)} \quad (2)$$

In this equation, QH denotes the charge derived from the integrated area of the hydrogen desorption peak (mC/cm²), $Qref$ is the standard reference charge density, and the applied catalyst loading is 0.5 mg/cm^2.

MEA testing on PEMFC single-stack

The performance of the MEA in the PEMFC was evaluated under varying humidifier temperatures, room temperature, 40 °C, 60 °C, and 80 °C while maintaining a constant hydrogen flow rate of 200 mL/min [18]. The optimal humidifier temperature was identified from this test using a single-stack PEMFC connected to the WonATech Smart 2 Fuel Cell Test Station.

Performance of MEA with various humidifier temperature

The performance of MEA PEMFC was investigated under varying humidifier temperatures, they were at room temperature, 40 °C, 60 °C, and 80 °C. The hydrogen flow rate was maintained throughout the experiments at a constant 200 mL/min. MEA performance was evaluated through polarization measurements, specifically by analysing the current density–voltage (I–V) and power density–current density (I–P) curves.

These polarization curves were used to determine the optimal humidifier temperature for PEMFC operation. Improved performance was indicated by a reduction in the slope of the polarization curve, reflecting a more gradual decline in voltage with increasing current density.

Performance of MEA with hydrogen flow rate analysis

The effect of hydrogen flow rate on the performance of MEA in a PEMFC was examined by varying the flow rate at 100 mL/min, 200 mL/min, 300 mL/min, and 400 mL/min. These tests were conducted under the previously identified optimal humidifier temperature. MEA performance at each flow rate was evaluated using polarization data, specifically through current density–voltage (I–V) and power density–current density (I–P) curves. The polarization curves also determined the most effective hydrogen flow rate, as indicated by a reduced slope or a flatter curve, which signifies enhanced fuel cell performance

RESULTS AND DISCUSSION

MEA Characterization using cyclic voltammetry (CV)

MEA measurements using Ti-Co/C and Pt/C catalysts in a single-stack PEMFC were conducted at a scan rate of 25 mV/s. At low scan rates, the process proceeds more slowly. However, it allows for better-defined voltammogram curves and improved capacitance. In contrast, higher scan rates result in faster voltammogram formation, but the quality of the voltammogram curves and the capacitance tends to be lower, shown in **Figure** 1.

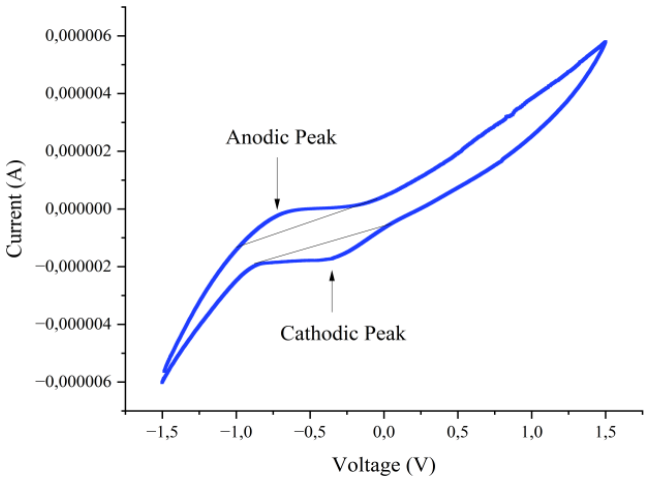

Figure 1. Voltammogram Curve of MEA

Figure 1 presents the voltammogram curve obtained from the CV characterization of the MEA using a Pt/C catalyst at the anode and a Ti-Co/C catalyst at the cathode. The curve shows an anodic peak at -0.877 V, corresponding to an electron release reaction, and a cathodic peak at -0.286 V, which represents an electron uptake reaction [19]. From the peak current values, the electrochemically active surface area (ECSA) of the Pt/C and Ti-Co/C-based MEA was calculated to be 8.38 cm^2/g. The observed anodic/cathodic features in the CV are consistent with redox transitions commonly reported for cobalt oxyhydroxide species in alkaline media ($Co(OH)_2 \leftrightarrow CoOOH$, Co^{2+}/Co^{3+}), while minor higher-potential features may reflect further oxidation to higher Co oxidation states. Titanium species in the composite are expected to act as structural or electronic modifiers rather than participating in the same redox chemistry within the studied potential window. Ti-oxide induced electronic modulation of Co active sites has been reported to shift redox potentials and enhance stability [20, 21].

MEA characterization using electrochemical impedance spectroscopy (EIS)

EIS is a widely used technique for analysing the kinetics and mechanisms of electrochemical systems by applying a small AC signal over a range of frequencies [17]. The data are typically analysed using the Nyquist plot, which displays one or more semicircular regions, reflecting the electrochemical activities occurring at the anode and cathode. In this study, the resulting curves were fitted to a mathematical model represented by an equivalent electrical circuit to determine the impedance values and conductivity of the MEA [3].

The fitting process yielded the values of Rp (Resistance polarization) and Rs (Resistance solution) to calculate the conductivity, in this analysis using NOVA software revealed the value of Rp and Rs at -8023 Ω and 80240 Ω appeared on Figure 2. The conductivity of the MEA was found to be 3.76×10^{-8} S/cm. The characterization was performed on the MEA, which contains an electrolyte membrane (Nafion). This membrane is an ionic conductor but electrically non-conductive, so its presence significantly lowers the overall measured electrical conductivity of the MEA [22]. A low impedance value indicates high electrical conductivity, whereas a high impedance value reflects low conductivity [23]. Based on the calculated conductivity value, the tested MEA demonstrates a reasonable ability to conduct electricity. This is because conductivity values within the range of 10^{-8} to 10^{2} S/cm fall under the category of semiconductors or materials capable of conducting electricity [24].

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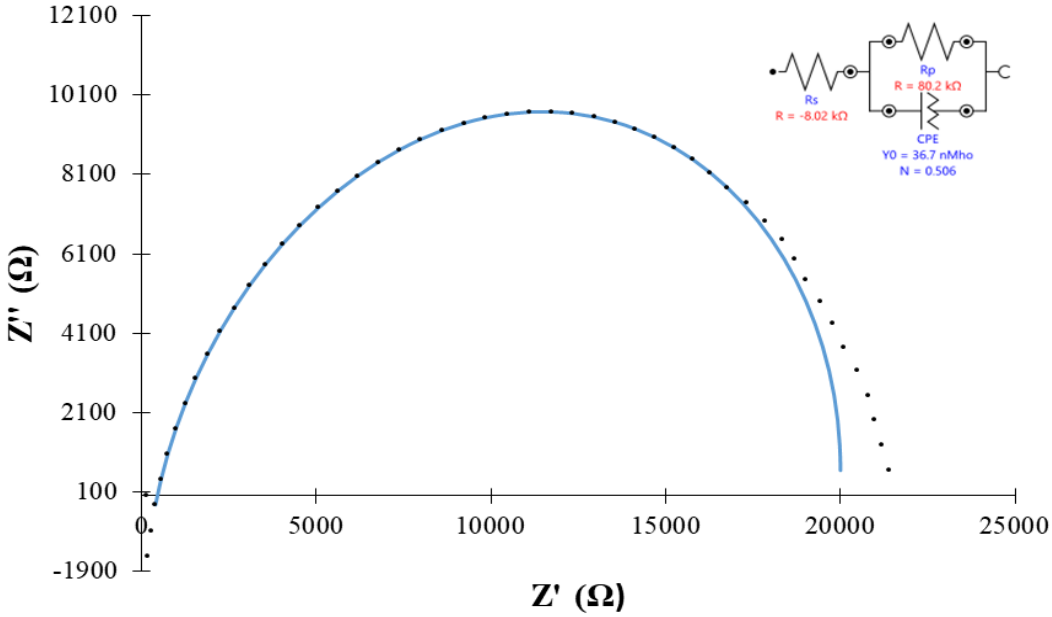

Figure 2. *Nyquist* of MEA

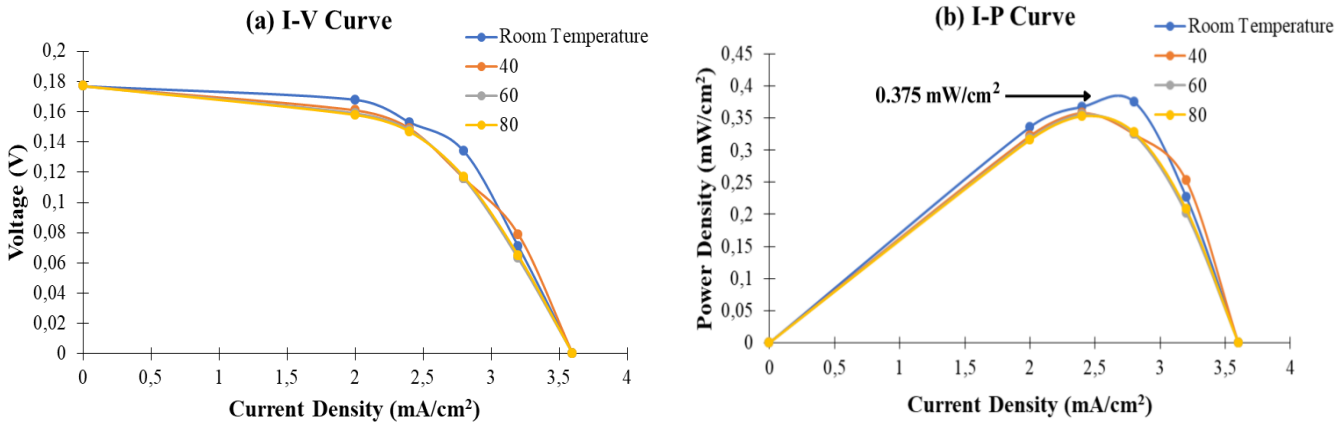

Figure 3. Performance of MEA on Humidifier Temperature (a) I-V (b) I-P

Influence of humidifier temperature on MEA performance

The optimal humidifier temperature has a significant impact on the performance of PEMFC. As a humidification method, it aims to keep the membrane adequately moist without excessive hydration, which can lead to membrane swelling. Controlling the humidifier temperature is also essential to determine the temperature at which the membrane reaches the ideal moisture level for optimal hydration [25].

The effect of humidifier temperature on MEA performance was evaluated by varying the temperature to room temperature (20 °C, 40 °C, 60 °C, and 80 °C), while maintaining a constant hydrogen gas flow rate of 200 mL/min. The performance test results of the MEA under different humidifier temperatures are presented in **Figure** 3.

The conclusion of **Figure** 3 (b) that the performance of MEA using the Ti-Co/C catalyst exhibited optimal hydration at room temperature, the maximum power density at 0.375 mW/cm^2 with a

current density of 2.8 mA/cm^2 (**Figure** 3 (a)). As it maintains voltage stability as the current load increases, compared with other humidifier temperature variations. At elevated humidifier temperatures ranging from 40 °C to 80 °C, the membrane tends to experience excessive moisture and warm vapor exposure, which can lead to rapid drying or dehydration. This condition reduces proton activity within the MEA, lowers its proton conductivity, and ultimately results in poor MEA performance [12].

Influence of hydrogen flow rate on MEA performance

After determining the optimal humidifier at room temperature, the subsequent MEA performance test was conducted by varying the hydrogen flow rate between 100 and 400 mL/min. The results are presented in the current density versus voltage curve, as shown in **Figure** 4. The hydrogen gas flow rate can enhance MEA performance when appropriately varied. An increased volume of hydrogen supplied as fuel contributes to improved performance of the MEA used [10].

The voltage versus current density curve in **Figure** 4 (a) at a hydrogen flow rate of 100 mL/min demonstrates a greater ability to maintain voltage under increasing current compared to other hydrogen flow rate variations. This flow rate also shows a more stable voltage during both activation and ohmic polarisation, preventing a drastic voltage drop as the current density increases [26].

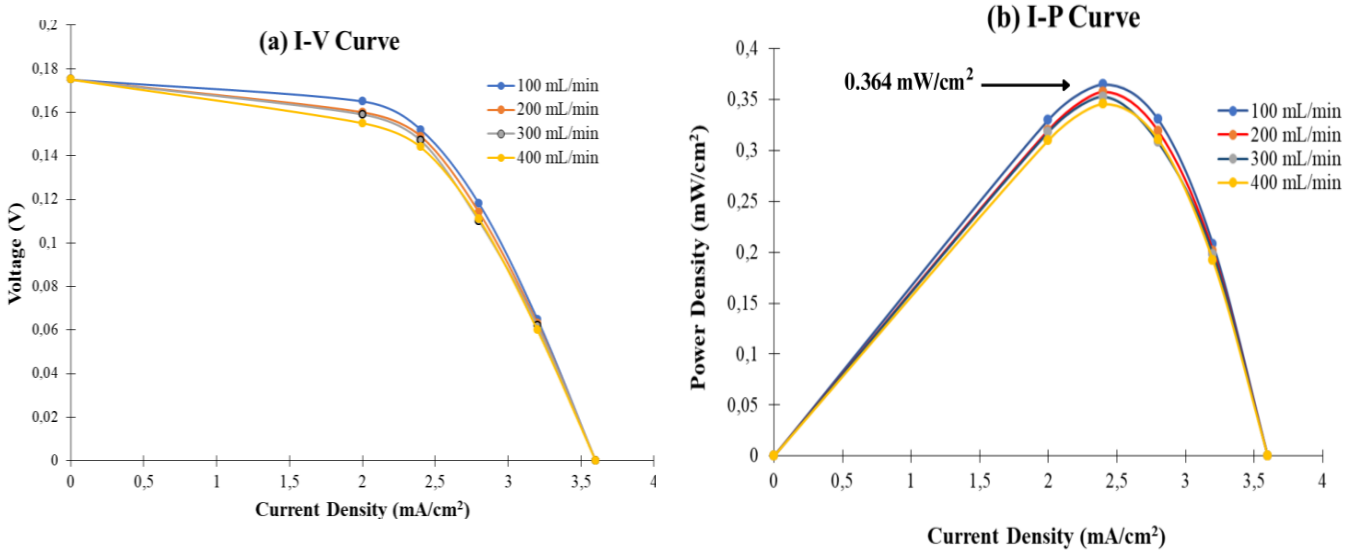

Figure 4. Polarization Response at Different Hydrogen Flow Rates (a) I-V (b) I-P

Figure 4 (b) shows that the MEA under investigation achieved its highest performance at a 100 mL/min hydrogen flow rate. This result is attributed to the more effective and uniform distribution of hydrogen at this flow rate compared to the other variations. An excessive hydrogen supply can lead to crossover, where the fuel passes through the membrane without undergoing the splitting process into protons and electrons [11], which can lead to corrosion to the supporting carbon due to water collecting to the pores of the electrode, the blockage can prevent the reactant from reaching the catalyst [27]. This phenomenon is associated with heat generation within the PEMFC stack, reducing overall performance. At the 100 mL/min flow rate, the MEA produced a power density of 0.364 mW/cm^2 and a current density of 2.4 mA/cm^2.

Intrinsic catalytic activity of non-PGM materials. Non-precious metal catalysts commonly show substantially lower ORR activity than Pt/C, while recent progress has narrowed the gap, practical single-cell power using many non-PGM cathodes remains lower without extensive optimisation. Recent reviews summarise the gap between PGM and PGM-free catalysts and the remaining challenges [28].

The obtained maximum power density is consistent with reported performances of non-PGM cathode catalysts tested under comparable conditions. As reviewed by Krishnan *et al.* [28], non-precious metal catalysts such as transition metal oxides and M-N-C typically exhibit much lower power densities than Pt-based systems, especially when catalyst structure and operating parameters are not optimized. Similarly, Jose *et al*. [29] was shown that humidifier temperature variation and oxidant flow significantly affect

maximum power point, demonstrating that fuel cell performance is sensitive to water management and mass transport. Furthermore, previous work by Rohendi *et al*. [30] confirmed that water imbalance and increased temperature can lead to conductivity loss and performance decline in MEA operation, reinforcing the interpretation that the relatively low power density observed here is consistent with expectations for non-PGM systems.

CONCLUSION

The characterization results of the Membrane Electrode Assembly (MEA) fabricated using Ti-Co/C and Pt/C catalysts with a catalyst loading of 0.5 mg/cm^2 showed an electrochemical surface area (ECSA) of 8.38 cm^2/g and an electrical conductivity of 3.76×10^{-8} S/cm. In evaluating the hydrogen gas flow rate, a 100 mL/min provided the best MEA performance, achieving a power density of 0.364 mW/cm^2 and a current density of 2.4 mA/cm^2. The influence of humidifier temperature also revealed that the MEA exhibited optimal performance at room temperature, with a power density of 0.375 mW/cm^2 and a current density of 2.8 mA/cm^2.Although these absolute power densities are lower than those typically achieved with Pt-based PEMFCs, they are within the expected range for non-PGM catalysts such as Ti–Co/C. The relatively low power density suggests that the catalytic activity of the Ti–Co/C formulation for the ORR remains limited and that improvements in catalyst dispersion and electrode structure are required to enhance the ECSA and overall electrochemical performance.

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REFERENCES

[1] J. Chen, Z. Ou, H. Chen, S. Song, K. Wang, and Y. Wang, "Recent developments of nanocarbon based supports for PEMFCs electrocatalysts," *Chinese Journal of Catalysis*, vol. 42, no. 8, pp. 1297–1326, 2021.

[2] B.H. Lim, E.H. Majlan, A. Tajuddin, T. Husaini, W.R.W. Daud, N.A.M. Radzuan, M.A. Haque, "Comparison of catalyst-coated membranes and catalyst-coated substrate for PEMFC membrane electrode assembly: A review," *Chinese Journal of Chemical Engineering*, vol. 33, pp. 1–16, 2021.

[3] N. Adhiyanti, D. Rohendi, N. Syarif, and A. Rachmat, "Preparation and Characterization of Ti-Co/C catalyst for PEMFC Cathode," *Indonesian Journal of Fundamental and Applied Chemistry*, vol. 6, no. 3, pp. 109–114, 2021.

[4] W. Yan, Y. Zhang, L. Chen, J. Luo, P. Pang, X. Zhang, B. Liao, M. Ying, "Corrosion behavior and interfacial conductivity of amorphous hydrogenated carbon and titanium carbide composite (aC: H/TiC) films prepared on titanium bipolar plates in PEMFCs," *Diamond and Related Materials*, vol. 120, p. 108628, 2021.

[5] I. Gatto, A. Saccà, R. Pedicini, E. Passalacqua, and A. Carbone, "Evaluation of titanium oxide introduction in the electrode structure for portable PEMFC applications," *International Journal of Hydrogen Energy*, vol. 46, no. 54, pp. 27687–27699, 2021.

[6] D. Rohendi, A. Rachmat, and N. Syarif, "Fabrication and Characterization of Pt-Co/C Catalyst for Fuel Cell Electrode," *Journal of Physics: Conference Series*, vol. 1095, no. 1, p. 012007, 2018.

[7] J. Zhao, H. Liu, and X. Li, "Structure, Property, and Performance of Catalyst Layers in Proton Exchange Membrane Fuel Cells", *Electrochemical Energy Reviews*, vol. 6, no. 1, p. 13, 2023.

[8] M. A. Ehsan, A.S. Hakeem, and A. Rehman, "Synergistic effects in bimetallic Pd–CoO electrocatalytic thin films for oxygen evolution reaction," *Scientific Reports*, vol. 10, no. 1, pp. 1–11, 2020.

[9] R. Kumar and K.A. Subramanian, "Enhancement of efficiency and power output of hydrogen fuelled proton exchange membrane (PEM) fuel cell using oxygen enriched air," *International Journal of Hydrogen Energy*, vol. 48, no. 15, pp. 6067–6075, 2023.

[10] B. Seo and H.K. Suh, "The Impact of Flow Rate Variations on the Power Performance and Efficiency of Proton Exchange Membrane Fuel Cells : A Focus on Anode Flooding Caused by Crossover Effect and Concentration Loss," *Energies*, vol. 18, no. 3084, pp. 1–27, 2025.

[11] R. E. Rosli, E.H. Majlan, S.A.A. Hamid, W.R.W. Daud, R. Mohammed, T. Husaini, D. Rohendi, "Study of hydrogen consumption by control system in proton exchange membrane

fuel cell," *Malaysian Journal of Analytical Sciences*, vol. 20, no. 4, pp. 901–912, 2016.
[12] Y. Chang, Y. Qin, Y. Yin, J. Zhang, and X. Li, "Humidification strategy for polymer electrolyte membrane fuel cells – A review," *Applied Energy*, vol. 230, pp. 643–662, 2018.
[13] T. Ma, K. Wang, Q. Zhou, W. Lin, M. Cong, and W. Jia, "Numerical study on humidification performance of fuel cell test platform humidifier," *Energies*, vol. 12, no. 20, 2019.
[14] Y. Li and M.J. Janik, "Recent progress on first-principles simulations of voltammograms," *Current Opinion in Electrochemistry*, vol. 14, pp. 124–132, 2019.
[15] N. Elgrishi, K.J. Rountree, B.D. McCarthy, E. S. Rountree, T.T. Eisenhart, and J.L. Dempsey, "A Practical Beginner's Guide to Cyclic Voltammetry," *Journal of Chemical Education*, vol. 95, no. 2, pp. 197–206, 2018.
[16] Y. Ashraf Gandomi, D.S. Aaron, Z.B. Nolan, A. Ahmadi, and M.M. Mench, "Direct measurement of crossover and interfacial resistance of ion-exchange membranes in all-vanadium redox flow batteries," *Membranes (Basel).*, vol. 10, no. 6, p. 126, 2020.
[17] A.C. Lazanas and M.I. Prodromidis, "Electrochemical Impedance Spectroscopy─A Tutorial," *ACS Measurement Science Au*, vol. 3, no. 3, pp. 162–193, Jun. 2023.
[18] D. Rohendi, N. Syarif, D. H. Yulianti, and N. R. Anjeli, "Effect of Humidifier Temperature and Hydrogen Flow Rate on MEA Performance of PEMFC Using Pt/C and Pd-Co/C Catalyst," *Malaysian Journal of Chemistry*, vol. 25, no. 5, pp. 223–229, 2023.
[19] D.H. Yulianti, D. Rohendi, N. Syarif, and A. Rachmat, "Performance Test of Membrane Electrode Assembly in DAFC using Mixed Methanol and Ethanol Fuel with Various Volume Comparison," *Indonesian Journal of Fundamental and Applied Chemistry*, vol. 4, no. 3, pp. 139–142, 2019.
[20] M.G. Kim and Y.H. Choi, "Electrocatalytic Properties of Co3O4 Prepared on Carbon Fibers by Thermal Metal–Organic Deposition for the Oxygen Evolution Reaction in Alkaline Water Electrolysis," *Nanomaterials*, vol. 13, no. 6, 2023.
[21] X. Zhu, Z. Zhao, J. Tang, X. Peng, H.D. Um, X. Li, Q. Xiao, W. Luo, "Elucidating the roles of oxygen defects-rich TiOxNy shell in Ti-based electrocatalyst for enhanced oxygen reduction reaction," *Fundamental Research*, vol. 5, no. 3, pp. 1134–1143, 2025.
[22] S. Li, R. Gu, R. Luo, X. Cheng, and X. Li, "Enhanced properties of Nafion nanofibrous proton exchange membranes by altering the electrospinning solvents," *Journal of Polymer Engineering*, vol. 44, no. 7, pp. 449–456, 2024.
[23] A. Kulikovsky, "A Fast Low-Current Model for Impedance of a PEM Fuel Cell Cathode at Low Air Stoichiometry," *Journal of The Electrochemical Society*, vol. 164, no. 9, pp. F911–F915, 2017.
[24] S.M. Sharaf, "Smart conductive textile," in *Advances in Functional and Protective Textiles*, Elsevier, 2020, pp. 141–167.
[25] V.M. Truong, N.B. Duong, C.-L. Wang, and H. Yang, "Effects of Cell Temperature and Reactant Humidification on Anion Exchange Membrane Fuel Cells," *Materials (Basel).*, vol. 12, no. 13, p. 2048, 2019.
[26] D. Zhu, Y. Yang, F. Pei, and T. Ma, "High-precision identification of polarization processes of distribution of relaxation times by polarization curve model for proton exchange membrane fuel cell," *Energy Conversion and Management*, vol. 268, p. 115994, 2022.
[27] J. Zhao, Z. Tu, and S.H. Chan, "Carbon corrosion mechanism and mitigation strategies in a proton exchange membrane fuel cell (PEMFC): A review," *Journal of Power Sources*, vol. 488, p. 229434, 2021.
[28] S. Rukmani Krishnan, D. Verstraete, and F. Aguey-Zinsou, "Performance of Non-Precious Metal Electrocatalysts in Proton-Exchange Membrane Fuel Cells: A Review," *ChemElectroChem*, vol. 11, no. 17, Sep. 2024.
[29] A. Jose, S. Bekal, and S.T. Revankar, "Effect of oxidant quantity and humidification temperature on performance of PEMFC with twin inlet and twin outlet flow field," *Frontiers in Energy Research*, vol. 12, pp. 1–13, 2024.
[30] D. Rohendi, E.H. Majlan, A. B. Mohamad, W.R.W. Daud, A.A.H. Kadhum, and L.K. Shyuan, "Effects of temperature and backpressure on the performance degradation of MEA in PEMFC," *International Journal of Hydrogen Energy*, vol. 40, no. 34, pp. 10960–10968, 2015.