Experimental study of the effect of hydrogen humidification on open-cathode PEMFC performance

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Abstract. Continuous efforts to develop environmentally friendly and renewable energy technologies are being undertaken in response to the increasing global energy demand. Proton exchange membrane fuel cells (PEMFCs) have emerged as an innovative alternative power source to replace conventional batteries, which generally have low power density. In this study, the hydrogen gas flow rate was varied and then humidified under three conditions: dry (without humidification), room temperature (~30°C), and heating (~40°C). Then, the polarisation curve was plotted as the main indicator of fuel cell performance, where the hydrogen flow rate was 25, 35, and 45 mL/min loaded with a constant current using a DC load. Based on the experiment, among the three conditions, the humidification mechanism (both at room temperature and heating) increased the measured voltage value, which had a correlation with fuel cell performance. The best condition was obtained when the bubble humidifier was controlled at a temperature of ~40°C, where a peak power density value of 0.133 mW/cm² was obtained. Overall, this study demonstrates that the combination of hydrogen flow rate control and heated humidification is an effective strategy to improve the performance stability of low-power passive open-cathode PEMFCs.

1 Introduction

Renewable energy is defined as energy derived from sources that are continuously replenished through natural processes. In contrast, conventional energy refers to energy obtained from finite and non-renewable sources, which are predominantly fossil-based. Currently, countries worldwide are striving to accelerate the energy transition from fossil fuels to new and renewable energy sources. Indonesia has set a target to achieve Net Zero Emissions (NZE) by 2060 as part of its commitment to supporting the global energy transition [1].

Proton Exchange Membrane Fuel Cells (PEMFCs) have emerged as an innovative alternative power source to conventional batteries due to their high power density, low operating temperature, and rapid startup capability [2-4]. A single PEMFC cell typically generates an output voltage ranging from approximately 0.6 V to 0.8 V under load and has a power output generally below 1 kW. PEMFCs operate by converting chemical energy—derived from pure hydrogen or hydrocarbons—into electrical energy through a series of electrochemical reactions, employing platinum (Pt) as the catalyst [5]. Structurally, a fuel cell consists of electrochemical cells composed of two bipolar plates, within which are integrated the anode and cathode catalyst layers, a polymer electrolyte membrane, and gas diffusion electrodes. One common PEMFC configuration is the open-cathode PEMFC, which utilizes ambient air as the oxidant and provide cooling for cell [6].

Open-cathode PEMFC systems are widely applied in portable electronic devices, unmanned aerial vehicles (UAVs), and small-capacity backup power supplies [7]. This configuration eliminates auxiliary subsystems such as active cooling, air humidification, and inlet pressure control, resulting in a simplified system architecture. However, this simplification leads to performance sensitivity, as the stack performance is strongly influenced by ambient temperature and humidity conditions [8].

Several studies have investigated the performance characteristics of open-cathode PEMFCs. Ling et al. (2016) examined an open-cathode PEMFC operating with high-purity hydrogen (99.9%) and fan-assisted oxygen supply, demonstrating that uniform cell temperature distribution enhances current generation and stack power output [2]. Wang et al. (2022) studied the effect of cathode flow field variations and reported that metal foam–based flow fields achieved superior polarization performance compared to parallel and pin-type designs [7]. Tu et al. (2025) investigated fan configurations at both the inlet and outlet of the cathode side, contrasting them with a single-sided air supply. Their findings demonstrated that achieving balanced airflow at both the cathode inlet and outlet leads to optimal voltage performance, improved temperature control and uniformity, as well as a 9.97% increase in stack output power [9]. Ahmaditaba et al. (2018)

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investigated the effects of humidifying the cathode side of a fuel cell. The air was humidified through a bubble humidifier mechanism, with the process controlled by adjusting the reservoir temperature, water depth inside the reservoir, and inlet air flow rate. The results indicated that an increase in the inlet air flow rate led to a reduction in relative humidity, measured between 6% and 11% [10].

Based on previous studies, research on open-cathode PEMFCs has focused extensively on the use of pure hydrogen, fan-assisted reactant supply, variations in flow fields, and strategies for managing airflow. This investigation study systematically examined the effects of humidified hydrogen gas at microflow rates of 25, 35, and 45 mL/min on the stability of fuel cell membranes. Additionally, fluctuations in the temperature of the distilled water within the humidifier were also examined to finds the optimum configuration for PEMFC performance.

2 Materials and Methods

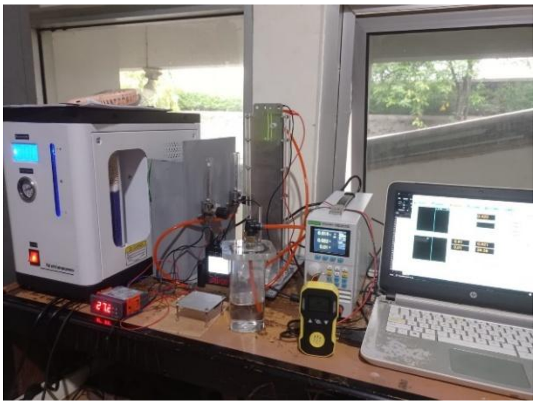
2.1 Materials

2.1.1 Set-up experiments

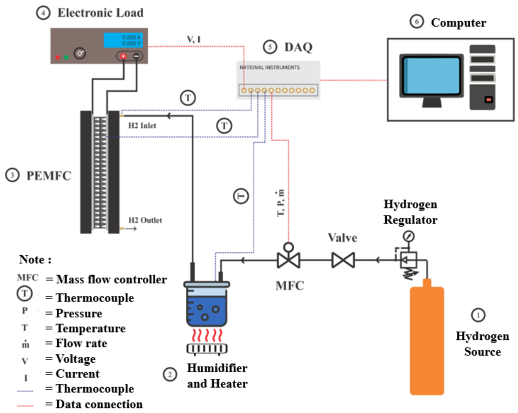
The experiment was conducted using a fuel cell with an active area of 190 cm². The fuel cell consisted of a single cell and used perfluorosulfonic acid (PFSA) as a membrane. The flow field design on the cathode side follows a straight pattern, while the anode side features a serpentine pattern. The anode side features two openings for the inlet and outlet of hydrogen gas fuel. Meanwhile, the cathode side is open for recirculating and cooling the fuel cell. Equipment that is used in this experiment is like a hydrogen generator with an output capacity of 300 ml/min (hydrogen purity 99,9%); a DC electronic load ET5410A+ (Hangzhou Zhongchuang Electron Co., Ltd, China); and a mass flow controller (MFC) Alicat MC-20SLPM (Alicat Scientific, Tucson, USA). Both of experimental set-up and schematic diagram of the PEMFC system is depicted in **Fig.1** .

Table 1. PEMFC spesification

Parameter	Value
Type	Open-cathode single cell
Active area	190 cm^2
Operation pressure	0.2 – 0.5 bar
Output voltage	0.5 – 0.63 VDC



(a) Experimental set-up



(b) Schematic diagram of the PEMFC system

Fig. 1. Experimental set-up and schematic diagram of the PEMFC system

The fuel cell used in this experiment was originally a stack-type cell produced by Ballard. The specifications of the fuel cell are presented in **Table 1**. It was subsequently reconfigured into a single cell featuring an open-cathode design. The current collectors on both the anode and cathode sides were secured using a clear acrylic plate, which is 1 cm thick, at the outermost part. Tightening is done using a number of nuts and bolts measuring M3, totalling 14 pieces.

2.1.2 Humidifier

The fuel cell system used an external humidification device in this experiment. This humidifier is employed to add moisture to the hydrogen gas prior to its entry into the fuel cell. The design of the humidifier features a bubble-type configuration, which is simply constructed from a borosilicate glass bottle with an acrylic lid that includes openings at the top. There are four ports provided: one for the hydrogen gas inlet connected to the hydrogen generator, one outlet port that delivers humidified hydrogen to the fuel cell, a port designated for replenishing distilled water, and a port for the insertion of a thermocouple sensor. Sealing was achieved with a high-temperature gasket, which provides protection against high temps when the bottle is heated. The temperature inside the bottle was automatically controlled by thermostat XH-W2028. The thermostat is connected to a heater plate (7.5 cm x 7.5 cm).

2.1.3 Heater

This investigation used of the active humidification system by an external heater plate that placed under the bubble humidifier tube. The utilization of an external heater plate guarantees conductive heat distribution via the walls of the borosilicate glass tube, different from internal heaters that pose a risk of polluting distilled water. XH-W2028 digital thermostat were used to control the temperature with a control precision of 0.1 °C and control range between -50°C and 110°C. Then, a k-type thermocouple sensor was immersed in distilled water to provide accurate temperature feedback, where the water was kept at a target temperature of 40 °C in order to maintain a consistent saturation vapor pressure during the test.

2.1.4 Mass flow controller

A mass flow controller regulates the flow rate of hydrogen gas supplied to the fuel cell. This MFC is equipped with software developed by the manufacturer FlowVision2. A few parameters that can be measured include mass flow, volumetric flow, and pressure. A temperature stability test of hydrogen gas flowing through the MFC was conducted over a duration of ± 4 hours, as illustrated in **Fig. 2**. The test was performed at ambient temperature ranging from 27 to 28°C.

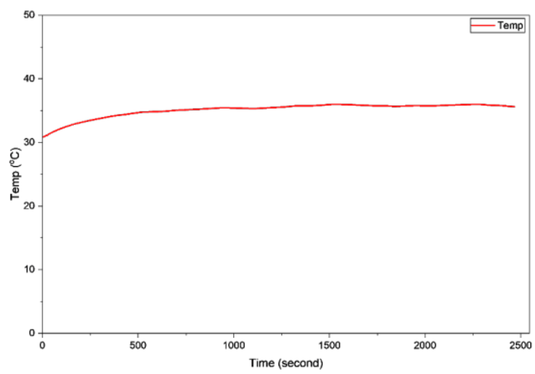


Fig. 2. Hydrogen gas temperature profile

2.2 Methods

2.2.1 Experimental design

In this study, two independent variables were variated to evaluate the performance of the open-cathode PEMFC ; the hydrogen mass flow rate and the reactant humidification state. The experimental matrix are presented in **Table 2** below.

Table 2. Experimental matrix for PEMFC test

Case	H_2 flow rate (mL/min)	Condition	Humidification temp. (°C)
1	25	Dry	-
		Room temp.	~ 30
		Heated humidification	40
2	35	Dry	-
		Room temp.	~ 30
		Heated humidification	40
3	45	Dry	-
		Room temp.	~ 30
		Heated humidification	40

The hydrogen flow rates were set at 25, 35, and 45 mL/min using MFC. For each flow rate, three humidification conditions were applied: (1) Dry, where hydrogen was supplied directly from the generator; (2) Room Temperature (RT), using a bubble humidifier without active heating; and (3) Heated, where the aquadest temperature inside the humidifier was maintained at 40°C using an XH-W2028 thermostat. The operating pressure was monitored at a constant ambient level of 0.994 barA via FlowVision software.

The experiment was carried out in the following way by each flow rate variation (25, 35, and 45 mL/min) and humidification condition was repeated three times (triplicate trials) to ensure data accuracy and reliability. The obtained data were then averaged to minimize the impact of random error and ensure that transient fluctuations, such as gas leaks, or bubble instability in the humidifier, did not disrupt the main data trend of polarization curve of the fuel cell which is being investigated.

2.2.2 Fuel cell preparation

The initial preparation of the experiment involved first connecting all tubing lines and device interfaces. The outlet of the hydrogen generator was connected to a mass flow controller (MFC) to allow adjustment of the hydrogen gas flow rate in response to variations in the research variables. Subsequently, the hydrogen gas from the MFC was directed to a bubble humidifier for humidification before being supplied to the fuel cell. The tubing was then connected to the anode inlet of the fuel cell. In addition to the tubing connections, electrical wiring was set up to enable data acquisition throughout the experiment. Data related to hydrogen gas flow rate, pressure, and temperature were recorded using the FlowVision™ 2 software (Alicat Scientific, Tucson, USA). Meanwhile, current, voltage, and power data were recorded using the LOAD software (Hangzhou Zhongchuang Electron Co., Ltd., China).

The fuel cell start-up process was initiated by ensuring that there were no hydrogen gas leaks at all connection points. Once safe operating conditions were confirmed, a purging process was conducted to remove residual air inside the cell. Subsequently, over a period of approximately 5 minutes, the cell voltage gradually increased until a stable voltage value (± 5 mV) was achieved [11]. The current load was then applied by setting the DC load to constant current mode, during which the maximum voltage level that could be sustained by the cell was gradually observed.

2.2.3 Humidity control

In this study, the humidity level of the PEMFC system was regulated using a bubble-type humidifier installed before the hydrogen gas enters the anode inlet. The procedure involves introducing H_2 gas into distilled water (5 cm depth of distilled water), resulting in direct interaction between the gas and liquid phases. This mechanism allows some of the water vapour to be carried by the hydrogen flow to the anode inlet, thereby helping to maintain the moisture content of the electrolyte membrane. This external humidification strategy is often used in PEMFCs operating at low temperatures because the water content in the membrane significantly affects the ability to conduct protons, the magnitude of the ohmic resistance, and the stability of the cell performance [12].

Thermodynamically, the partial pressure of the water vapour carried in the hydrogen stream is controlled by adjusting the temperature of the distilled water in the humidifier. The temperature of the distilled water is controlled using a thermostat. Based on Raoult's Law, the partial pressure of water vapour can be expressed as

$$P_{H2O} = x_{H2O} \times P_{sat} \quad (1)$$

$$RH = [P_{H2O} / P_{sat}\,(T_{gas})] \times 100\% \quad (2)$$

The liquid medium used is distilled water, where the mole fraction of water approaches one. Therefore, under equilibrium conditions, the partial pressure of water vapour is determined by the saturated vapour pressure of water as a function of temperature [13]. Therefore, increasing the temperature of the distilled water will increase its hydrogen flow capacity to carry water vapour to the anode side of the PEMFC. The assumption used is that the measured hydrogen flow rate in the MFC represents the flow rate entering the anode side of the fuel cell, as losses due to condensation and pressure drop are considered insignificant.

2.2.4 Heating

Heating was one of the experimental conditions evaluated to determine the initial performance characteristics of the fuel cell. The heating process was conducted without direct contact by utilizing an XH-W2028 thermostat connected to a heater plate. The bubble humidifier bottle was placed on top of the heater plate to increase the temperature of the distilled water inside the humidifier. The thermostat was operated in heating mode with a temperature setpoint of 40 °C and automatically turned off once the target temperature was reached.

2.2.5 Polarization curve characterization

Electrochemical performance characteristics of the Open Cathode PEMFC were analyzed using polarization curve and power density curve. The polarization curve is an in-situ analysis method for assessing the performance of a PEMFC. This curve is a plot of voltage versus current density, measured under steady-state or dynamic conditions [14]. The test was conducted by gradually drawing a constant current load from the open circuit voltage (OCV) condition until the cut-off voltage of 0.1 volts was reached. Each variation data was taken after the cell reached a steady state with a waiting time interval of 5 minutes. This aims to ensure the stability of the reactant distribution and water management in the flow field. The obtained data were then averaged to analyze the resistance events that occurred in each loss region. The slope of the curve in the linear region was used to analyze the ohmic resistance of the cell, while the voltage drop at high current was used to evaluate the limitations of mass transfer in this fanless natural convection system.

3 Results and Discussion

3.1 Effects of flow rate variation

Fig. 3 presents the polarization and power density curves of a PEMFC at varying hydrogen flow rates of 25, 35, and 45 mL/min. From the experiment, the open circuit voltage (OCV) values at all three flow rates range from 0.80 to 0.82 V. However, all curves display similar characteristics of PEMFCs, where the cell voltage decreases as the current density increases. Additionally, regarding power density, the cell voltage initially rises to a peak before subsequently decreasing at higher current densities. Then, when maximum current density is achieved, the voltage drops to between 0.41 and 0.44 V. This trend illustrates the combined effects of activation losses at low current densities, ohmic losses in the intermediate range, and mass transport limitations at elevated current densities.

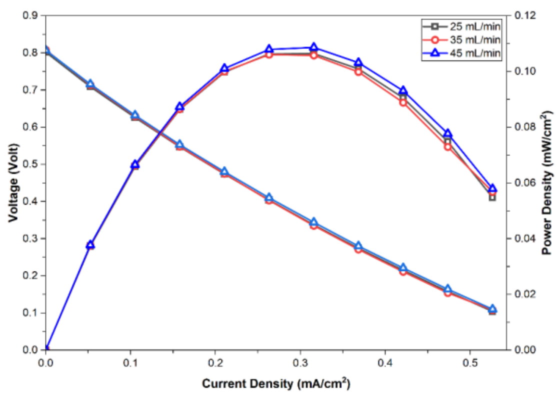


Fig. 3. Polarization curve for hydrogen flowrate variation

All three variations in hydrogen gas flow rate produced relatively similar polarization behavior, indicating that increasing the hydrogen flow rate does not significantly improve PEMFC performance. The slightly higher voltage and power density at 45 mL/min indicate that increased hydrogen availability, but the differences are quite small. Therefore, cell performance is most likely not affected by hydrogen supply, but rather by internal electrochemical losses, primarily membrane hydration and ohmic resistance. Adequate membrane hydration is crucial for maintaining proton conductivity, while poor water management can increase ohmic losses or cause flooding-related mass transport resistance.

Also on the graph, when the medium current is around 0.26–0.31 mA/cm², the maximum power density is obtained with a value of around 0.105–0.110 mW/cm². After this peak condition, the power density slowly decreases because the voltage drop is more dominant than the increase in current density. This indicates the beginning of the mass transport limitation phase, where the delivery of reactants and/or water accumulation becomes a bottleneck for the electrochemical reaction rate. In open cathode PEMFCs, several conditions that can affect this decrease are due to fluctuations in ambient air supply, evaporation, and water imbalance in the membrane-electrode assembly.

3.2 Effects of humidified gas

Fig. 4 shows the polarisation curve and power density data from varying flow rates of humidified hydrogen gas at room temperature (approximately 30°C) without heating. The experiment obtained an average open circuit voltage (OCV) of approximately 0.81 V. This bubbling process demonstrates that the bubble humidifier is capable of providing sufficient humidity to maintain membrane stability in the initial reaction stage, even without external heating. Based on Raoult's Law, at 30°C, the partial pressure of water vapour is sufficient to provide basic hydration, which reduces the ohmic resistance compared to dry cell conditions.

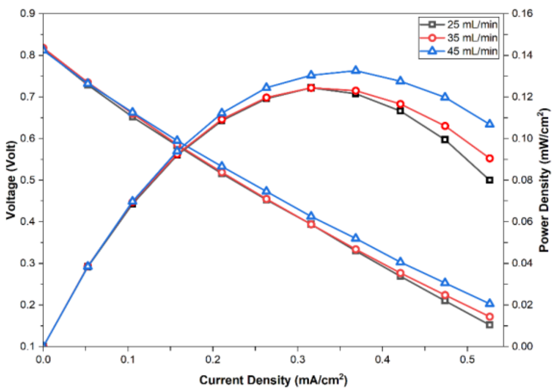


Fig. 4. Polarization curve for humidified gas

Based on the observed flow rate variations, a flow rate of 45 mL/min produced the highest power density, with a peak value of ~0.132 mW/cm². Meanwhile, at flow rates of 25 mL/min and 35 mL/min, the profiles overlap in the low- to medium-current region but begin to differentiate in the mass transport region (>0.36 mA/cm²). At a flow rate of 25 mL/min, it also appears to exhibit behaviour where the earliest performance decline occurs, indicating fuel starvation due to the gas flow rate not being strong enough to drive water accumulation.

The results presented in **Fig. 4** indicate that increasing the hydrogen flow rate to 45 mL/min have a better performance response compared to flow rates of 25 and 35 mL/min. This enhancement is likely attributable to a combination of a more sufficient hydrogen supply, improved distribution of reactants at the anode, and the gas flow's capacity to mitigate water accumulation, which can decrease the performance of the fuel cell, such as through flooding.

3.3 Effects of heated gas

The polarisation and power density curve plots of the varying flow rates of humidified hydrogen gas at 40°C with heating treatment are shown in **Fig. 5**. In this experiment, the open circuit voltage (OCV) values were obtained in the range of 0.81-0.82 V. The use of an external heater (heater plate with thermostat) aimed to increase the saturated hydrogen vapour pressure before it enters the anode. Overall, the maximum power density under these conditions reached its highest point compared to previous tests, reaching approximately 0.134 mW/cm² at a flow rate of 35 mL/min. The highest power density is achieved at a hydrogen flow rate of 35 mL/min, while the lowest is observed at 45 mL/min.

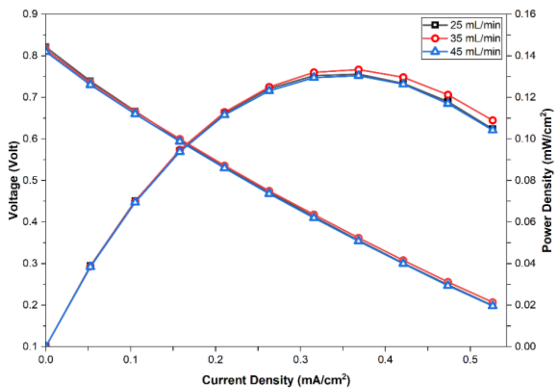


Fig. 5. Polarization curve for heated gas

Furthermore, there is an interesting observation in this graph. The overall voltage value at a flow rate of 45 mL/min is lower than that at 35 mL/min. This may be due to the shorter residence time of H_2 in the bubble humidifier. Consequently, even though the distilled water in the humidifier is at 40°C, the H_2 gas may not achieve the same humidification conditions as at 35 mL/min. Water temperature, gas residence time, water column height, and bubble size all influence the RH of the gas in a bubble humidifier. Reducing the gas-water contact time can decrease the actual water vapour content carried by H_2, resulting in slightly lower membrane hydration. A less hydrated membrane will have a higher proton resistance, resulting in a decrease in cell voltage due to increased ohmic loss. The increasing gas temperature causes the amount of distilled water that can be accommodated also increase, so that it is very likely to lead to flooding conditions on the membrane.

Additionally, excessively high H_2 flow rates can accelerate the transport of water vapour out of the anode. Under certain conditions, a flow rate of 45 mL/min can lead to partial membrane dry-out, particularly in open-cathode PEMFCs where the cathode side experiences evaporation due to contact with the surrounding air.

3.4 Maximum peak power density

Fig. 6 illustrated the peak power density of the entire experiment matrix. A consistent trend of increasing power is seen as the humidification temperature increases from dry conditions to 40°C. At a flow rate of 35 mL/min, a temperature increases from room temperature to 40°C which increases the maximum power by 7.25%. Furthermore, the graph shows that although the 45 mL/min flow rate has the highest potential for reactant flow, its performance stability at high temperatures is greatly influenced by the mechanical side of the cell, where the 35 mL/min flow rate proved to be the most balanced operating point between hydration and fuel consumption.

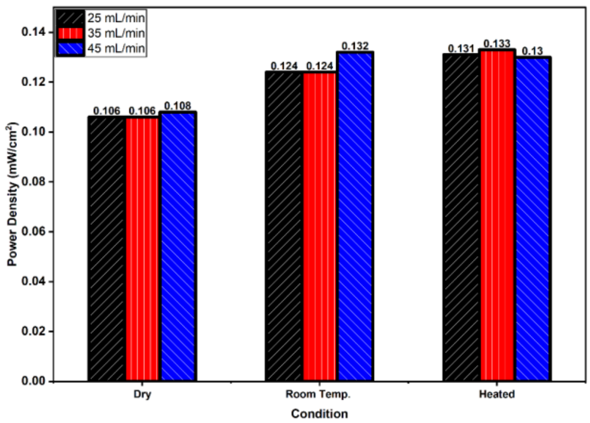


Fig. 6. Peak power density comparation

3.5 Cell temperature of the fuel cell

Graphs of cell temperature versus time are presented in **Fig. 7, Fig. 8** and **Fig. 9**. The graphs show that the PEMFC temperature remained relatively stable throughout the test under all operating conditions. At all hydrogen flow rate variations, the cell temperature remained within the range of approximately 29.8–30.8°C, with relatively small fluctuations throughout the test duration. This indicates that the system operated under near-isothermal conditions. Consistent with this, the performance changes observed in the polarization curves are more likely influenced by humidification conditions, membrane hydration, ohmic resistance, and mass transport, rather than changes in cell temperature.

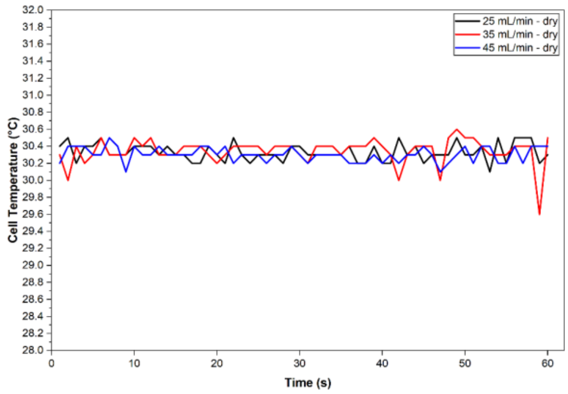


Fig. 7. Cell temperature at dry condition

At **Fig. 7**, under dry conditions, the cell temperature remained stable without significant temperature increases, indicating that the heat generated during operation did not cause significant thermal changes in the passive open-cathode PEMFC system. A similar pattern was also observed under room temperature and 40°C humidification conditions, where the differences between hydrogen flow rates were relatively small. Thus, the temperature data support that the primary influence of this experiment comes from water management and reactant supply.

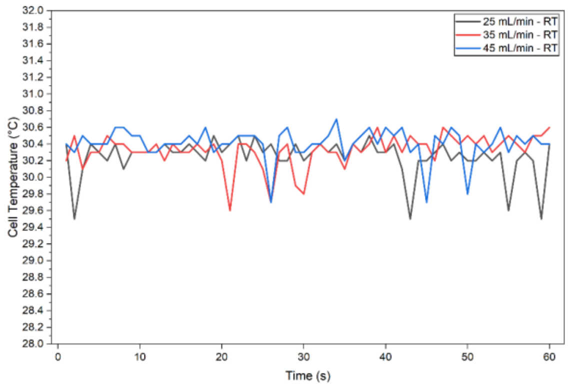


Fig. 8. Cell temperature at room temp. humidification

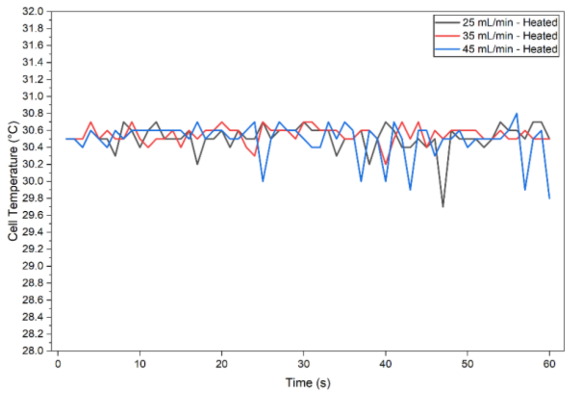


Fig. 9. Cell temperature at 40℃ humidification

4 Conclusions

This study evaluated the effect of varying hydrogen flow rate and humidification conditions before entering the anode inlet of a PEMFC. The measured ambient pressure was 0.994 barA. Experiments revealed that a humidification mechanism using a heating treatment with a temperature control of 40°C provided the best and most significant results. The peak power density obtained was ~0.133 mW/cm². Variations in hydrogen flow rate revealed that increasing the reactant supply to 45 mL/min could support hydrogen availability on the anode side. However, increasing the flow rate did not always result in a proportional increase in voltage. This condition indicates that cell performance is influenced by many aspects, in addition to the nominal hydrogen supply, which are also influenced by humidification effectiveness, reactant distribution, mass transport, and the mechanical integrity of the fuel cell. Thermal analysis showed that the cell temperature during testing was in the range of 29.8–30.8°C, so the system can be considered to operate under near-isothermal conditions.

Overall, the results of this study indicate that the integration of external heated humidification and precise hydrogen flow rate control can improve the performance stability of passive open-cathode PEMFCs through membrane hydration optimisation. The best operating conditions in this study were obtained at 40°C humidification, with medium- to high-hydrogen flow rates that still need to be controlled to avoid reactant supply imbalances or gas losses due to sealing limitations. These results offer an experimental foundation for the advancement of a more stable, straightforward, and efficient low-power portable PEMFC system devoid of supplementary fans.

M. S. Taufiqurrahman: Conceptualization, Methodology, Investigation, Visualization, Writing – original draft. H. M. Ariyadi: Conceptualization, Resources, Supervision, Writing – review & editing. H. Suripto: Conceptualization, Methodology, Resources. R. D. D. Putra: Supervision, Methodology. Deendarlianto: Validation, Supervision, Funding acquisition.

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