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Effects of electrolyte temperature and voltage input on the hydrogen production rate of a polymer electrolyte membrane electrolyzer

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ABSTRACT

This paper analyses the limiting effects of temperature and voltage on the hydrogen production rate and Faraday efficiency of a single-cell Proton Exchange Membrane (PEM) electrolyzer that operates without an active membrane humidity control. The analysis is based on the problem of identifying the optimal operating conditions for the system setup mainly due to membrane dehydration that leads to ohmic losses. The experiments are conducted under controlled laboratory conditions for distilled water temperature variations (25 to 50°C) and input voltage variations (1.8V to 3.6V). The key outputs are hydrogen production rate and Faraday efficiency. The results indicate that the MEA humidity is normal up to 45ºC, but the hydrogen production kinetics loss is 14% at 50ºC due to membrane dehydration. The potential loss due to membrane humidity at the manufacturer limit of 60ºC is estimated at 16% through data regression approach. However, operating the electrolyzer at room temperature gives a strong performance relative to voltage variation where the Faraday efficiency is between 84 to 95%. The evaluation indicates that the PEM electrolyzer operation is optimally balanced for hydrogen output, energy input and system safety operations between 25 to 40ºC and a voltage between 2.4 to 3.0V.

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1. INTRODUCTION

Hydrogen is being viewed as a central component in the transition to cleaner and more sustainable energy systems. Hydrogen can exist as a zero-carbon carrier of energy if it is generated and utilized under the right conditions. Out of various techniques of hydrogen production—steam methane reforming, gasification of biomass, and photochemical reactions—water electrolysis stands apart in its ability to generate very high purity hydrogen from electricity and water directly. This process is especially promising whenpowered by renewable energy sources such as solar and wind, enabling a fully green supply chain.

Water electrolysis involves splitting watermolecules into hydrogen and oxygen gases using electrical energy. Ttraditional alkaline electrolysers use a liquid electrolyte and normally potassium hydroxide (KOH) is the chosen chemical, known to be low cost but with slower electrochemical dynamics when compared to other electrolysers [1]. Proton exchange membrane (PEM) electrolysers use a solid polymer electrolyte that conducts protons. They have typical features of high current densities, compact design, and fast response time with high hydrogen production efficiency. However, it is costly due to the use of platinum metal catalysts [2]. Alkaline Electrolyte Membrane (AEM) electrolysers combines features of both PEM and alkaline systems; they also use a a conducting polymer membrane, but for hydroxide ions. Currently in development, this technology is touted to be cheaper with higher efficiencies [3].

Among the various types of electrolysers, PEM electrolysers are often preferred due to their high efficiency, compactness, fast response time, and ability to operate under high-pressure conditions [4]. The PEM electrolyzer is compact in size, responds quickly, and can accommodate variable renewable energy sources. A PEM device utilizes a liquid-free solid polymer membrane (typically Nafion), which selectively conducts protons and acts as a barrier to gas crossover, enablingefficient and safe operation even at elevated pressures [5]. The use of PEM electrolyzers in small- and large-scale hydrogen systems has received increasing attention due to their scalability and compatibility with renewable energy inputs. The efficient design of PEM electrolyzer stacks, including flow field geometry and electrode assembly, significantly influences hydrogen production rates and system longevity [6]. A range of parameters controls the performance of PEM electrolysers including voltage, water conductivity, membrane hydration, current density, and temperature [7].

PEM electrolysers use distilled water as the electrolyte. Distilled water has a low ionic conductivity and, therefore, less current flow and hydrogen generation rates unless compensated with other system operating conditions. Kruger and Dresselhaus [8] indicated that the use of distilled water tends to slow system response and reduce gas evolution rates unless offset by higher temperatures or voltages. Barbir [6] emphasized the use of proper thermal and electrical control in the handling of non-enhanced electrolytes. Therefore, understanding how system parameters such as voltage and temperature influence system behaviour is essential to optimize performance.

Temperature is a critical parameter that affects both reaction kinetics and membrane ionic conductivity, playing a dual role in enhancing performance. Firstly, it increases ionic conductivity through the membrane, thereby reducing ohmic losses. Secondly, it lowers the activation energy required for electrochemical reactions. Operating a PEM system at high temperatures (a maximum of 60°C) can significantly improve overall efficiency [9]. However, exceeding the thermal limit can lead to membrane dehydration, hence reducing performance due to increase in proton transport resistance. The electrochemical reaction rate constant increases exponentially with temperature according to the Arrhenius equation, thereby reducing the activation energy barrier for proton conduction and gas evolution [10].

In practice, the practical voltage exceeds the thermodynamic limit of 1.23 V to compensate for losses caused by activation overpotential, ohmic resistance, and concentration gradient [11]. However, extremely

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high voltages may also result in thermal degradation of membrane components and reduced Faraday efficiency as a result of energy loss [12]. The Faraday efficiency, defined as the ratio of electrical energy input to chemical hydrogen energy output, depends on current input and cell resistance. It is usually maximum at intermediate current densities when ion transport losses are minimal and overpotential loss is low [13]. PEM electrolyser efficiency can reach 90–95% under ideal conditions, while in practical applications it typically ranges between 70 and 90%. [14]. A major factor contributing to reduced efficiency, especially at high voltage and temperatures, is membrane dehydration,which lowers hydrogen production rates due to mass transport limitations within the membrane [12].

One of the fundamental issues of PEM electrolysis is system's sensitivity to operating parameters such as input voltage, electrolyte temperature, and current density. This paper reports the electrical voltage and distilled water electrolyte temperature influence on hydrogen production using a PEM electrolyzer setup. The electrolyzer consists of a single-cell Nafion membrane electrode assembly (MEA). By comparing experimental values to theoretical predictions on the basis of Faraday's law, the analysis highlights the inefficiencies of the PEM cell relative to ideal operating conditions. The results provide a systematic approach to evaluatingoptimal voltage and temperature conditions for a small-scale PEM electrolyser system.

2. METHODOLOGY

This research focuses on the experimental and theoretical study of the production of hydrogen using a PEM electrolyzer system using distilled water as a medium under various thermal and electrical conditions. The first part of the methodology explains the experiment setup, while the second part discusses the Faraday law model that governs the electrolysis process.

2.1 Experimental Setup

The hydrogen generation system (refer to Figure 1) is based on a compact, single-cell, PEM electrolyzer. The power input to the electrolyzer is designed to allow variable voltage input using a regulated DC power supply. A refrigerated bath circulator was used to obtain the required distilled water temperature prior to electrolysis. The hydrogen output was measured using a calibrated syringe connected to the hydrogen outlet. Table 1 lists the experiment setup component description and specifications.

The experiment is divided into two phases – (1) temperature variation at fixed voltage and (2) voltage variation at fixed current. For the temperature variation experiment, the process starts by preparing 45 mL distilled water at the desired temperature (25°C, 30°C, 35°C, 40°C, 45°C, and 50°C) using the bath circulator (refer Figure 2). The water is then fed into the PEM electrolyzer, where the DC power supply voltage is set constant at 3.6V under non-constant current. The timer stopwatch is started when the power supply is turned on. Hydrogen is generated at the cathode and the 20 mL syringe acts as a hydrogen storage tank. The hydrogen outlet from the electrolyser has been modified to connect directly to the syringe nozzle. When the experiment starts, the syringe piston is closed (zero volume) and as hydrogen fills the syringe through the nozzle, the piston expands according to the gas volume. By visual inspection, the stopwatch records the time when the generated hydrogen has filled the syringe to the 20 mL level. The power supply is turned off, and the hydrogen is then purged from the syringe to the atmosphere. A fresh batch of distilled water is then heated in the bath circulator at a new temperature, and the procedure is repeated. The experiment at each temperature is repeated 3 times to ensure results consistency.

For the voltage variation experiment, the temperature of the distilled water is set at room temperature (28oC). The current is kept constant at 0.5A, while the circuit voltage is adjusted to specific values (1.8 V, 2.4 V, 2.8 V, 3.2 V, and 3.6 V), and the timer is started. The time to completely fill the 20 mL syringe is recorded. The system is turned off, and the hydrogen is purged from the syringe. A new voltage is then

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applied, and the procedure is repeated. The process is repeated three times at each voltage to ensure data reliability. Due to the small-sized MEA (less than 10 cm^2), and limitations of the rated power supply output, the scope of analysis focuses on hydrogen output with respect to voltage changes for clearer interpretation.

The experimental hydrogen production rate (in mL/s) is evaluated using the volume of gas collected (20 mL for all cases) and the time taken for each case,

$$\text{Production Rate} = \frac{V_{H_2}}{t} \tag{1}$$

where V_{H2} = volume of hydrogen gas (20 mL), and t = filling time in seconds.

Due to the flammable nature of hydrogen, safety protocols are observed where the work is conducted in a ventilated room to prevent the accumulation of hydrogen gas. Care is exercised to avoid any sources of open fire or electrical sparks near the equipment during use.

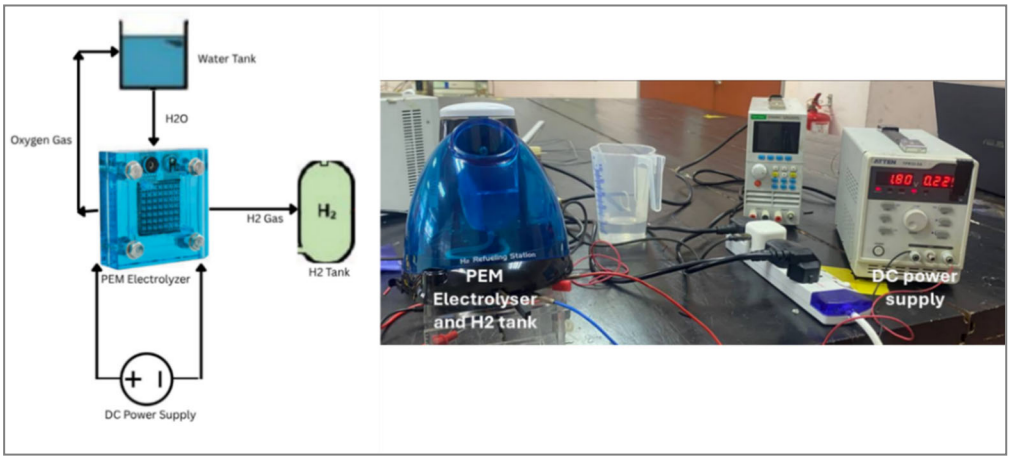

Fig. 1. Schematic and system setup of the single-cell PEM electrolyser

Table 1. Component description and specifications

Component	Description
PEM Electrolyzer	Horizon i-H2GO station with Membrane Electrode Assembly (MEA) size 18 mm x 18 mm (9.72 cm²)
DC Power Supply	Adjustable (0–5 V, capped at 0.5 A) for input voltage variation
Refrigerated Bath Circulator	Lab Companion RW-0525G
Electrolyte	Distilled Water
Hydrogen Collection	Syringe connected to the hydrogen outlet port
Thermometer	Digital Extech 421305
Timer	Manual stopwatch to measure hydrogen filling period

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Fig. 2. Refrigerated bath circulator for electrolyte temperature control

Several simplifying assumptions are made to enable experimental simplification and theoretical consistency:

i. It is assumed that the system is at a constant atmospheric pressure of 1 atm.
ii. The response of the gases involved was in accordance with ideal gas assumptions.
iii. It is assumed that there is minimal loss of hydrogen by leakage so that direct volumetric measurement of the generated gas could be made without adjustment.
iv. A state of constant current is assumed in every measuring cycle such that Faraday's law could be utilized reliably in efficiency calculations.
v. The power supply limit—capped at 3.6 V and 0.5 A—makes it impossible to test higher current densities or voltages, which could have provided additional information about performance trends beyond the range tested.

2.2 Electrochemical Theory and Equations

Figure 3 illustrates the structure and operation of a PEM electrolyzer, with key components such as the membrane, electrodes, gas outlets, and electrical contacts labelled. The fundamental electrochemical reactions involved in water electrolysis at the PEM electrolyzer are:

At the anode (oxidation): $2H_2O\ (l) \rightarrow O_2\ (g) + 4H^+ + 4e^-$ (2)

At the cathode (reduction): $4H^+ + 4e^- \rightarrow 2H_2\ (g)$ (3)

Overall cell reaction: $H_2O\ (l) \rightarrow H_2\ (g) + \frac{1}{2}\ O_2\ (g)$ (4)

Voltage, or cell potential, is the driving force for water splitting in PEM electrolysis. The theoretical reversible voltage required for water electrolysis under standard conditions is 1.23 V, representing the Gibbs free energy change [15]. Practically, however, additional voltage must be applied to compensate for losses such as activation overpotential, ohmic losses, and mass transport resistance [16]. The performance of the membrane, including proton transport and degradation under cyclic conditions, plays a crucial role in determining electrolyzer durability [17]. The hydrogen generation rate is regulated by applied voltage, with theoretical behaviour described by activation overpotential theory and empirical trendline models.

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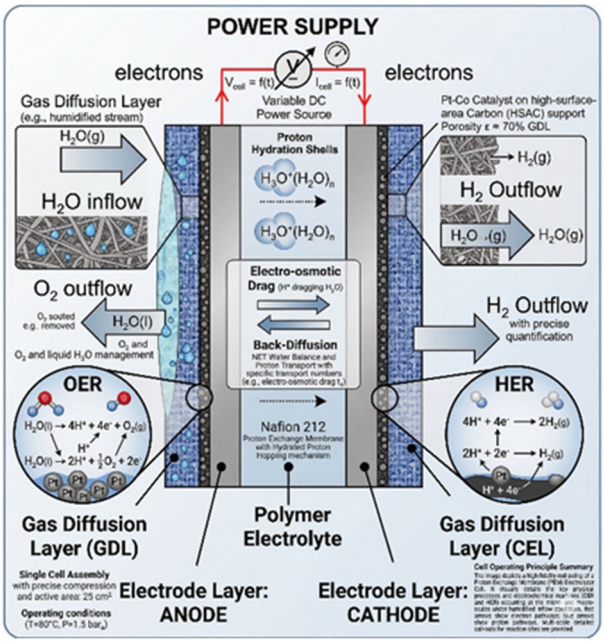

Fig. 3. PEM electrolyzer structure and operation

The underlying electrochemical kinetics of such behaviour are defined by means of the Butler-Volmer equation with incorporation of the activation overpotential term,

$$i = i_0 \left[\exp\left(\frac{\alpha_a F \eta_{act}}{RT} \right) - \exp\left(-\frac{\alpha_c F \eta_{act}}{RT} \right) \right] \tag{5}$$

where i = current density (A/m^2), i_0 = exchange current density, αa, αc = anodic and cathodic charge transfer coefficients, η_{act} = activation overpotential (V), F = Faraday's constant (96485 C/mol), R = universal gas constant (8.314 J/mol.K), and T = temperature in Kelvin (K).

To analyse the energy conversion performance, Faraday efficiency (η_F - also known as current efficiency) is a critical metric in water electrolysis that quantifies the fraction of electrical charge successfully converted into hydrogen gas. It is defined as the ratio of the actual moles of hydrogen produced to the theoretical moles predicted by Faraday's law of electrolysis. While ideal systems would achieve 100% Faraday efficiency, practical systems experience losses due to gas crossover, parasitic side reactions, and electronic leakage, especially at high current densities [14].

$$\eta_F = \frac{n_{\text{actual}}}{n_{\text{theoretical}}} \times 100\% \tag{6}$$

where n_{actual} is the moles of hydrogen measured experimentally from the syringe volume using the ideal gas law,

$$n_{actual} = \frac{PV}{RT} \tag{7}$$

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and $n_{theoretical}$ is the theoretical moles of hydrogen produced,

$$n_{theoretical} = \frac{I.t}{2F} \tag{8}$$

where P is the absolute pressure of hydrogen (in kPa) which is assumed at atmospheric pressure (100 kPa) and V is the volume produced (20 mL).

Temperature is an important parameter in electrochemical reactions, where the performance of the PEM electrolyzer improves with temperature due to enhanced proton conductivity of the membrane, faster charge transfer kinetics, and lower activation overpotentials [18]. According to the Arrhenius equation, higher temperatures reduce the energy barrier for reaction initiation, thereby increasing the rate of hydrogen production.

$$k = A.e^{-\frac{E_a}{RT}} \tag{9}$$

where k is the rate constant, A is the pre-exponential factor, Ea is the activation energy (J/mol), R is the universal gas constant (8.314 J/mol·K), and T is the absolute temperature in Kelvin.

3. RESULTS AND DISCUSSION

3.1 Temperature Effect on Hydrogen Generation

The results presented in this section is based on temperature variation of distilled water under constant applied voltage of 3.6 V. The experimental data is summarized in Table 2. Additionally, at fixed voltage, the circuit current varies dynamically within the range of 0.7 V to 0.8 V according to the micro changes in the reaction electrochemistry and component resistances. For each water temperature, three samples of the time to fill 20 mL of hydrogen in the syringe is averaged and the hydrogen production rates are calculated. Statistical analysis shows that the standard deviation across the samples is between 1.4 to 3.3% from its average time and is acceptable for further analysis.

Figure 4 shows the profiles of the hydrogen filling period and production rate as the water electrolyte temperature increases. Hydrogen production increases at a constant rate of 7% at low water temperatures mainly due to greater energy for a rapid charge transfer kinetics across the membrane [19]. However, at 45ºC, the hydrogen production rate increases by nearly 30% from the rate at 40ºC, indicating it has reached a state where the energy barrier for reaction initiation is significantly lowered.

The hydrogen production rate profile from 25 to 45ºC water temperature follows an exponential trend, closely aligning with the Arrhenius equation. However, experiments show that there is a nearly 10% reduction in hydrogen production rate at 50ºC compared to at 45ºC. The ideal profile of the hydrogen production rate from 25 to 45ºC water temperature predicts that the production rate at 50ºC should increase by 12%, or from 0.1227 to 0.1374 mL/sec. However, the experiment produces a hydrogen decline to 0.1111 mL/sec. This reduction is theoretically caused by membrane dehydration that limits the charge transfer between the electrodes due to lower water molecules within the membrane for proton transport. Dehydrated membranes possess lower ionic conductivity, which negates the kinetic advantages of higher temperatures [20].

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Table 2. Experimental data on 20 mL hydrogen production time across variations in water temperature (constant 3.6V)

Temperature (ºC)	Sample 1 (min:sec)	Sample 2 (min:sec)	Sample 3 (min:sec)	Average Time (sec)	H2 Production Rate (ml/s)
25	5:30	5:05	5:18	318	0.0629
30	5:10	5:01	4:50	275	0.0727
35	4:42	4:34	4:30	240	0.0833
40	4:05	3:59	3:56	209	0.0957
45	3:25	3:38	3:26	163	0.1227
50	2:42	2:43	2:46	180	0.1111

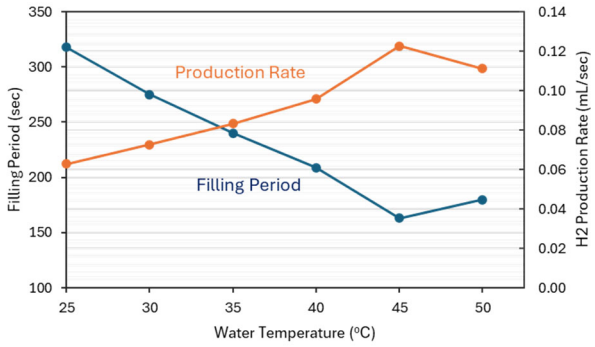

Fig. 4. Hydrogen filling period and production rates profile due to temperature variation

The optimal operating temperature for a low temperature Nafion MEA is 60ºC, which occurs before dehydration at elevated temperature that limits proton conductance and lowers the hydrogen production rate. Figure 5 shows the profiles of hydrogen production rate under ideal and actual membrane conditions from the experimental data. Based on the theoretical Arrhenius equation, the ideal profile is a power regression curve based on data from 25 to 45ºC water temperature where the membrane is assumed to be hydrated, whereas the actual profile is the power regression curve based on data until 50ºC where the membrane is under dehydration.

At 50ºC, a hydrated membrane would theoretically produce 0.14 mL/sec of hydrogen, whereas a dehydrated membrane would only produce 0.12 mL/sec of hydrogen, which is translated to a 14% hydrogen production rate loss due to membrane dehydration that leads to higher ionic resistance. The loss increases as the temperature rises, where a predictive profile at 60ºC (recommended operating temperature) indicates that the loss would increase by to 2% to 16%. This analysis leads to the conclusion that the membrane quality of this PEM electrolyzer has deteriorated, either due to service life factor or material engineering fault, and should be replaced for better performance. These findings are consistent with previous experimental work by Ito et al. [12] and Grigoriev et al. [7], which reported the same performance thresholds in thermal imbalance and membrane degradation at elevated temperatures.

Overall, the findings confirm that moderate heating of the electrolyte enhances hydrogen production, but exceeding the thermal threshold leads to membrane dehydration and long-term performance degradation.

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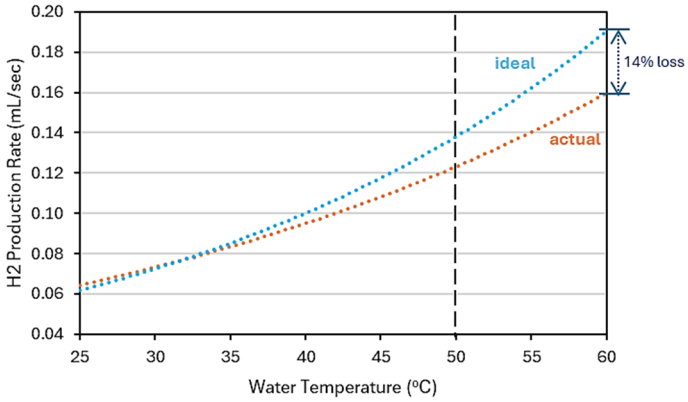

Fig. 5. Regression profiles of the hydrogen production rate under ideal and actual PEM cell conditions

3.2 Voltage Effect on Hydrogen Generation

Theoretically, water decomposition to hydrogen and oxygen requires a minimum thermodynamic voltage of 1.23 V under standard conditions, although additional voltage is needed to overcomesystem losses. As the applied voltage increases, the hydrogen generation rate also increases due to the accelerated electrochemical kinetics and enhanced current flow [6]. Table 3 lists the three-sampling data taken for hydrogen filling period at each voltage (from 1.8 V to 3.6 V), its average time and hydrogen production rate. The standard deviation range of each voltage variation is 0.3% to 1.2%, which indicates the experiment reliability. Notably, the current drawn also increases with voltage, from 0.2 A at 1.8 V to 0.5 A at 3.6 V, reflecting Ohm's Law. Figure 6 plots the average filling time and production rate against the circuit voltage. The hydrogen production profile follows the Arrhenius law on electrolysis, with a power curve profile. The production of hydrogen at each voltage is very low at low voltage, taking approximately 30 minutes to generate 20 mL of hydrogen. The filling period reduces exponentially at higher voltage due to higher vell potential to overcome the activation energy and ohmic resistance. By doubling the voltage to 3.6V, the time needed reduces by half to approximately 11 minutes.

The hydrogen production power curve profile demonstrates that while increasing voltage enhances gas production, the rate of electrochemical reactions slows as the system becomes limited by internal resistance and mass transport [21]. High voltages in PEM electrolyzers would lead to higher hydrogen generation, but Carmo et al. [5] stated that it will result in higher membrane degradation rates and gas crossover. Moreover, Grigoriev et al. [7] emphasized the necessity between operating voltage and system lifetime balance. For a single-cell, long operations above 3 V in the absence of humidity control potentially distorts membrane performance. During this study, the I-H2GO PEM electrolyzer without humidification control showed a stable production rate at high voltages of 3.0 to 3.6V, indicating that the MEA is properly hydrated in operations at low electrolyte temperature.

Faraday efficiency (also known as current efficiency) is a metric in water electrolysis that quantifies the fraction of electrical charge successfully converted into chemical energy in the form of hydrogen gas. It is defined as the ratio of the actual moles of hydrogen produced to the theoretical moles predicted by Faraday's law (Eq. 6). While ideal systems would achieve 100% Faraday efficiency, practical systems experience losses due to gas crossover, parasitic side reactions, and electronic leakage, especially at high current densities [14].

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Table 3. Experimental data on hydrogen production time across variations in electrolyser voltage

Voltage (V)	Current (A)	Sample 1 (sec)	Sample 2 (sec)	Sample 3 (sec)	Average Time (sec)	Production Rate (ml/s)
1.8	0.2	1880	1638	1849	1789	0.0112
2.2	0.3	1308	1284	1230	1274	0.0157
2.4	0.35	1230	1102	1050	1097	0.0182
2.6	0.4	848	860	1050	876	0.0228
2.8	0.4	810	796	799	801	0.0250
3.0	0.5	721	714	719	718	0.0279
3.6	0.5	690	660	719	689	0.0295

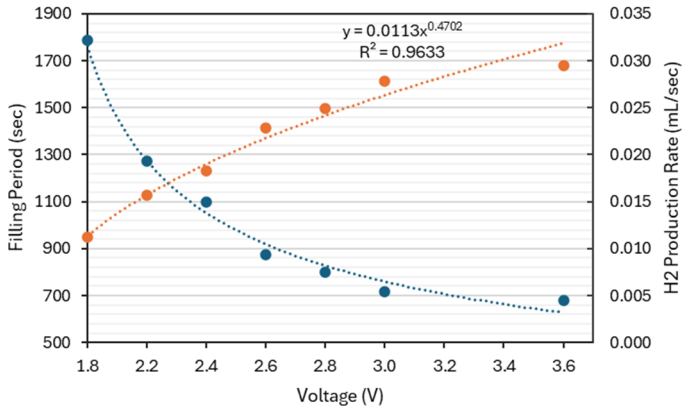

Fig. 6. Hydrogen filling period and production rates profile due to voltage variation

Faraday efficiency for constant electrolyte temperature is evaluated using both theoretical (Faraday's law) and experimentally derived moles of hydrogen, assuming ideal gas behaviour at atmospheric pressure and ambient temperature. The Faraday efficiency (refer Table 4 and Figure 7) range is between 84% to 95%, where the efficiency can be profiled to increase linearly at low voltages (1.8 to 3.0V) before it approaches a constant efficiency at higher voltages due to limitations in mass transport.

These findings suggest that for a single-cell PEM electrolyzer, an optimal voltage range of 2.4 to 3.0V produces the most efficient stability and hydrogen yield trade-off. Beyond this range, the hydrogen production rate increase is at the expense of unnecessarily overloading the system. This is in agreement with the findings of Siracusano et al. [22], where voltage optimization has been recognized as an essential design parameter of PEM electrolysis.

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Table 4. Ideal and actual moles of hydrogen produced and Faraday efficiency

Voltage (V)	Current (A)	Refilling Time (s)	Ideal Moles (mol)	Actual Moles (mol)	Faraday Efficiency (%)
1.8	0.2	1880.2	0.00195	0.001676	86%
2.2	0.3	1274.0	0.00198	0.001676	85%
2.4	0.35	1097.3	0.00199	0.001676	84%
2.6	0.4	876.3	0.00182	0.001676	92%
2.8	0.45	801.7	0.00187	0.001676	90%
3.0	0.5	718.0	0.00186	0.001676	91%
3.6	0.5	678.3	0.00176	0.001676	95%

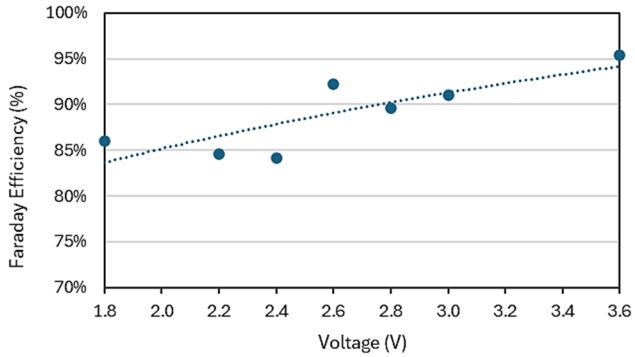

Fig. 7. Faraday efficiency profile as the applied voltage varies

4. CONCLUSION

This study explores the effects of input voltage and electrolyte water temperature on hydrogen production in a single-cell PEM electrolyser. The experimental results demonstrate the sensitivity of the MEA to both voltage and temperature variations. The single-cell PEM effectively generates hydrogen at low temperatures, but critical membrane dehydration occurs at 50°C which severely reduces the hydrogen production rate. As such, the PEM electrolyser assembly could not reach the designated operating temperature of 60°C without incurring additional hydrogen production rate losses. When the electrolyte temperature is low at ambient, voltage variation tests proves that the MEA works efficiently. The optimal temperature of this PEM electrolyser is limited between 25 to 40°C where dehydration is expected to increase ionic losses significantly after 40°C. Voltage variation tests at constant temperature, with Faraday efficiency ranging from 84% to 95%. The variation of different voltage levels reveals the optimal, energy efficient, voltage is between 2.4 to 3.0V, providing a compromise between gas output, energy requirement and system safety. The response to temperature and voltage change is consistent with electrochemical theory and literature-reported trends where the presented analysis offers a systematic understanding on the effects of thermal and electrical factors in limiting the electrochemical reactions of water electrolysis using a PEM electrolyzer.

The measured filling time for both experiment sets are different at similar voltage and water temperature, as can be noted for the experiment at 3.6 V and 28°C from Tables 2 and 3. This is caused by

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the limiting current of 0.5A on the 2nd experiment, whereas the 1st experiment does not set a limiting current and the current varies based on the reaction conditions, typically in the range of 0.7 A to 0.8 A. Therefore, the time needed to produce 20 mL of hydrogen in the 2nd experiment takes a longer time due to the low current applied.

5. ACKNOWLEDGEMENTS/FUNDING

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6. CONFLICT OF INTEREST STATEMENT

The authors agree that this research was conducted in the absence of any self-benefits, commercial or financial conflicts and declare the absence of conflicting interests with the funders.

7. AUTHORS' CONTRIBUTIONS

Muhammad Syazwan developed the test setup, performed the experiments, analysed the data and wrote the draft of the article. **Wan Ahmad Najmi Wan Mohamed** conceptualised the central research idea, provided the theoretical framework. supervised research progress, revised and approved the article submission.

8. REFERENCES

[1] W. Li, H. Tian, L. Ma, Y. Wang, X. Liu, and X. Gao, "Low-temperature water electrolysis: fundamentals, progress, and new strategies," *Materials Advances*, vol. 3, no. 14, pp. 5598–5644, 2022, doi: https://doi.org/10.1039/D2MA00185C.

[2] Rajangam Vinodh, Shankara Sharanappa Kalanur, Sadesh Kumar Natarajan, and B. G. Pollet, "Recent Advancements of Polymeric Membranes in Anion Exchange Membrane Water Electrolyzer (AEMWE): A Critical Review," *Polymers*, vol. 15, no. 9, pp. 2144–2144, Apr. 2023, doi: https://doi.org/10.3390/polym15092144.

[3] N. Du, C. Roy, R. Peach, M. Turnbull, S. Thiele, and C. Bock, "Anion-Exchange Membrane Water Electrolyzers," *Chemical Reviews*, vol. 122, no. 13, pp. 11830–11895, Apr. 2022, doi: https://doi.org/10.1021/acs.chemrev.1c00854.

[4] J. A. Turner, "A Realizable Renewable Energy Future," *Science*, vol. 285, no. 5428, pp. 687–689, Jul. 1999, doi: https://doi.org/10.1126/science.285.5428.687.

[5] M. Carmo, D. L. Fritz, J. Mergel, and D. Stolten, "A comprehensive review on PEM water electrolysis," *International Journal of Hydrogen Energy*, vol. 38, no. 12, pp. 4901–4934, Apr. 2013, doi: https://doi.org/10.1016/j.ijhydene.2013.01.151.

[6] F. Barbir, "PEM electrolysis for production of hydrogen from renewable energy sources," *Solar Energy*, vol. 78, no. 5, pp. 661–669, May 2005, doi: https://doi.org/10.1016/j.solener.2004.09.003.

[7] J. Hwang, C.-H. Lin, and J.-K. Kuo, "Performance analysis of fuel cell thermoelectric cogeneration system with methanol steam reformer," *International Journal of Hydrogen Energy*, vol. 39, no. 26, pp. 14448–14459, Sep. 2014, doi: https://doi.org/10.1016/j.ijhydene.2014.01.109.

https://doi.org/10.24191/esteem.v22iMarch.9858

[8] S. A. Sherif, D. Yogi Goswami, E.K. (Lee) Stefanakos, and A. Steinfeld, *Handbook of Hydrogen Energy*. CRC Press, 2014

[9] D. Pletcher and F. C. Walsh, "Industrial electrochemistry (second edition)," *Journal of Chemical Technology and Biotechnology*, vol. 52, no. 3, pp. 427–428, Jan. 1991, doi: https://doi.org/10.1002/jctb.280520317.

[10] P. Millet, "Fundamentals of Water Electrolysis". *Electrochemical Energy Systems*, pp. 33–62, 2015. doi: 10.1002/9783527676507.ch2.

[11] A. S. Tijani and A. H. A. Rahim, "Numerical Modeling the Effect of Operating Variables on Faraday Efficiency in PEM Electrolyzer," *Procedia Technology*, vol. 26, pp. 419–427, 2016, doi: https://doi.org/10.1016/j.protcy.2016.08.054.

[12] S. P. Sanaka, K. Ramanaiah, and P. Vanni, "Performance Analysis Of Pem Electrolyser For Green Hydrogen Production," *Sustainable Chemistry for Climate Action*, p. 100162, Nov. 2025, doi: https://doi.org/10.1016/j.scca.2025.100162.

[13] B. Yodwong, D. Guilbert, M. Phattanasak, W. Kaewmanee, M. Hinaje, and G. Vitale, "Faraday's Efficiency Modeling of a Proton Exchange Membrane Electrolyzer Based on Experimental Data," *Energies*, vol. 13, no. 18, p. 4792, Sep. 2020, doi: https://doi.org/10.3390/en13184792.

[14] D. Bessarabov, H. Wang, H. Li, and N. Zhao, Eds., "PEM Electrolysis for Hydrogen Production," Feb. 2016, doi: https://doi.org/10.1201/b19096.

[15] S. Shiva Kumar and V. Himabindu, "Hydrogen Production by PEM Water Electrolysis – A Review," *Materials Science for Energy Technologies*, vol. 2, no. 3, Dec. 2019, doi: https://doi.org/10.1016/j.mset.2019.03.002.

[16] C. G. Vayenas, R. E. White, M. E. Gamboa-Aldeco, and Springerlink (Online Service, *Modern Aspects of Electrochemistry 42*. New York, Ny: Springer New York, 2008.

[17] A. M. I. Noor Azam *et al.*, "Parametric Study and Electrocatalyst of Polymer Electrolyte Membrane (PEM) Electrolysis Performance," *Polymers*, vol. 15, no. 3, p. 560, Jan. 2023, doi: https://doi.org/10.3390/polym15030560.

[18] J O'm Bockris, *Modern electrochemistry : volume 2A : Fundamentals of electrodics*. New York: Plenum Press, 2000.

[19] S. J. Paddison and R. Paul, "The nature of proton transport in fully hydrated Nafion®," *Physical chemistry chemical physics/PCCP. Physical chemistry chemical physics*, vol. 4, no. 7, pp. 1158–1163, Feb. 2002, doi: https://doi.org/10.1039/b109792j.

[20] F. Scheepers *et al.*, "Temperature optimization for improving polymer electrolyte membrane-water electrolysis system efficiency," *Applied Energy*, vol. 283, p. 116270, Feb. 2021, doi: https://doi.org/10.1016/j.apenergy.2020.116270.

[21] A. Mohd *et al.*, "Investigation of Performance of Anion Exchange Membrane (AEM) Electrolysis with Different Operating Conditions," *Polymers*, vol. 15, no. 5, pp. 1301–1301, Mar. 2023, doi: https://doi.org/10.3390/polym15051301.

[22] S. Siracusano *et al.*, "Optimization of components and assembling in a PEM electrolyzer stack," *International Journal of Hydrogen Energy*, vol. 36, no. 5, pp. 3333–3339, Mar. 2011, doi: https://doi.org/10.1016/j.ijhydene.2010.12.044.

https://doi.org/10.24191/esteem.v22iMarch.9858