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DYNAMIC TEMPERATURE-DEPENDENT SIMULATION OF A 400-CELL PROTON EXCHANGE MEMBRANE FUEL CELL STACK USING MATLAB-SIMSCAPE

Wan Ahmad Saffuan bin Wan Mohamed Salleh[1] & Sahriah Basri[1]*

[1]*Fuel Cell Institute, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia*

**Corresponding author:* sahriah@ukm.edu.my

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Abstract

Proton exchange membrane fuel cells (PEMFCs) are promising clean energy converters for stationary and mobility applications, but their performance is strongly governed by thermal and water balance under dynamic load operation. This study extends a previously developed thesis model into a journal-level dynamic assessment by introducing four clearly defined inlet-temperature cases (40, 50, 60 and 70 °C), applying an identical transient load profile to every case, consolidating electrochemical and balance-of-plant outputs, and evaluating the resulting operating window using coupled performance, thermal, water-production and hydrogen-consumption criteria. The model represents a 400-cell PEMFC stack with an active area of 280 cm2 per cell and a constant hydrogen supply pressure of 70 MPa. Model credibility was examined through physical-consistency checks and comparison of the predicted trends with established PEMFC behaviour reported in the literature. Increasing inlet temperature improved high-current polarization response and power stability, with 70 °C producing the strongest high-current tolerance. However, this benefit was accompanied by greater thermal stress: although all cases approached a quasi-steady stack temperature of approximately 353 K, the peak stack temperature increased from 353 K at 40 °C to 364 K at 70 °C. Dynamic current density reached approximately 0.95 A cm-2, heat generation peaked at about 37-40 kW, water production reached about 10 g s-1 and hydrogen consumption reached about 1.1 g s-1 during peak demand. The results identify 60-70 °C as the most practical operating range, with 60 °C providing the more conservative balance between performance and thermal margin. Experimental validation remains necessary before the model is used for quantitative design or control-system certification.

Keywords: PEMFC; MATLAB-Simscape; dynamic load; operating temperature; hydrogen consumption; thermal management; water management

1. Introduction

Proton exchange membrane fuel cells (PEMFCs) are among the most mature electrochemical energy conversion technologies for hydrogen-based power generation. Their low operating temperature, fast start-up, relatively high power density and zero local emission profile make them attractive for clean transport, backup power, distributed generation and renewable energy integration [1,2]. Despite these advantages, reliable PEMFC deployment is still constrained by coupled electrochemical, thermal and mass-transport limitations. Temperature is one of the most influential operating variables because it affects electrode kinetics, proton conductivity, membrane hydration, reactant transport, water removal and component degradation.

In a PEMFC, hydrogen oxidation occurs at the anode and oxygen reduction occurs at the cathode. The membrane must remain sufficiently hydrated to transport protons effectively, while gas diffusion layers and flow channels must remove product water without starving the catalyst layer of reactants. Under low-temperature operation, reaction kinetics can be slower and water accumulation may lead to flooding. At excessively high temperature, improved kinetics may be offset by membrane dehydration, increased ohmic resistance and accelerated material degradation [3-5]. Therefore, the optimum temperature cannot be defined only by the highest power output; it must also consider thermal stability, water balance and fuel utilisation.

Many PEMFC studies use steady-state polarization curves to compare performance. However, practical fuel-cell systems rarely operate at a constant load. Applications such as vehicles, portable power systems and grid-support devices experience repeated load fluctuations, which cause transient changes in current density, voltage, heat generation, hydrogen consumption and water production. These dynamic effects are important for sizing the cooling system, humidifier, hydrogen supply and control strategy. Simulation platforms such as MATLAB-Simscape are useful because they allow rapid evaluation of the system-level response before experimental prototyping, reducing cost and enabling safer operating-window exploration [6-8].

The present paper extends the earlier thesis model in four specific ways. First, it replaces the broad thesis-level reporting of numerous individual outputs with a controlled four-temperature comparison under one identical dynamic load cycle. Second, it integrates polarization, voltage, current density, stack temperature, heat generation, water production and hydrogen consumption in a single coupled assessment rather than interpreting these outputs separately. Third, it evaluates the temperature range against a practical operating-window criterion that considers both power response and balance-of-plant requirements. Fourth, it adds an explicit model-credibility assessment based on governing physical relationships, internal consistency and comparison with published PEMFC trends. The objective is to determine the most suitable inlet-temperature range for a 400-cell PEMFC stack under dynamic load and to clarify the implications for cooling, humidification, reactant supply and future experimental validation.

2. Model Configuration and Simulation Method

A system-level PEMFC stack model was implemented in MATLAB-Simscape. The model included the hydrogen source, oxygen source, anode and cathode gas channels, anode and cathode humidifiers, exhaust subsystems, recirculation path, cooling system, membrane electrode assembly and electrical load. The membrane electrode assembly block represented a 400-cell stack with an active area of 280 cm2 per cell. The principal independent variable was the inlet temperature, set at 40, 50, 60 and 70 °C. Although conventional low-temperature PEMFC stacks are commonly operated within approximately 60-80 °C, the lower 40 and 50 °C cases were retained as diagnostic boundary conditions. They allow the model to quantify the penalty associated with sub-optimal cold operation and to distinguish kinetic and water-management effects before the stack reaches its normal operating range. The hydrogen supply pressure was kept constant at 70 MPa to isolate the effect of temperature within the configured system.

The same dynamic load profile, simulation duration, initial conditions and balance-of-plant settings were applied to all four temperature cases. Recorded variables were stack voltage, stack temperature, current density, heat generated or dissipated, electrical power, water production and hydrogen consumption. Polarization and power-density curves were used to assess electrochemical response, while time-domain outputs were used to evaluate transient stability and the severity of thermal, water and reactant-supply requirements. Unlike the thesis, which presented a wider collection of model outputs, the present analysis uses a common comparison framework and focuses only on variables that directly support operating-window selection.

2.1 Improvements relative to the thesis model

The underlying stack architecture remains based on the thesis model, but the journal version improves the analysis and interpretation rather than claiming a completely new electrochemical formulation. The principal improvements are: (i) a controlled temperature-sweep design using identical dynamic inputs; (ii) simultaneous interpretation of electrochemical, thermal and mass-balance outputs; (iii) direct comparison of 40-70 °C to identify the transition from cold, kinetically limited operation to the conventional PEMFC operating range; and (iv) an engineering decision framework that distinguishes a high-performance set point from a conservative durability-oriented set point. These additions convert the thesis model from a general simulation platform into a focused operating-window study.

2.2 Model verification and validation approach

Model verification was performed through three levels of consistency checking. First, the predicted polarization response was examined for the expected sequence of activation, ohmic and mass-transport losses. Second, the dynamic outputs were checked for physical coupling: increases in current demand had to coincide with lower voltage, higher heat generation, greater hydrogen consumption and greater product-water formation. Third, the temperature trends were compared qualitatively with established PEMFC theory and published studies, which generally report improved reaction kinetics and voltage retention as temperature rises toward the normal 60-80 °C operating range, subject to adequate membrane hydration [4,12-15]. The simulated peak current density of approximately 0.95 A cm^{-2} and the observed improvement from 40 to 70 °C are therefore physically plausible. However, these checks constitute trend-level validation only. Because matched experimental data for the same 400-cell stack and dynamic load cycle were not available, the model should not yet be treated as quantitatively validated as shown in Table 1. This distinction is retained throughout the discussion and defines the present limits of model use.

Table 1. Summary of PEMFC stack model and simulation variables.

Parameter	Value used in simulation	Purpose in analysis
Number of cells	400	Stack-level voltage and power evaluation
Active area per cell	280 cm2	Current-density and power-density assessment
Hydrogen supply pressure	70 MPa	Kept constant to isolate temperature effect
Inlet temperature	40, 50, 60 and 70 °C	Main independent variable
Recorded outputs	Voltage, current density, power, heat, water and H2 use	Dynamic performance and system sizing
Software platform	MATLAB-Simscape	Physics-based system simulation

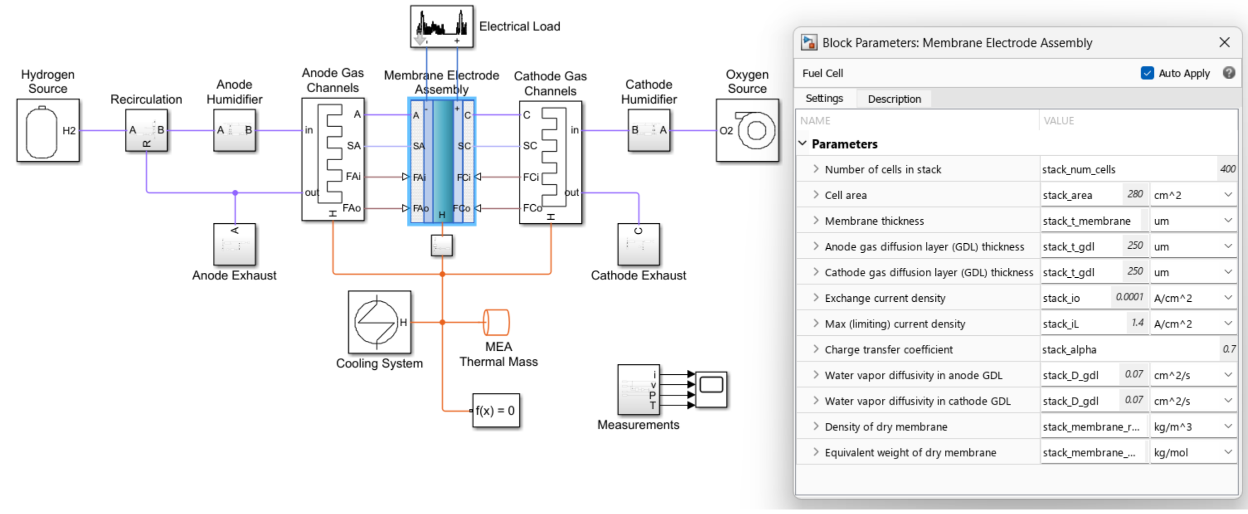

Figure 1. MATLAB-Simscape PEMFC stack configuration used in the simulation, showing the hydrogen and oxygen supply paths, gas channels, humidifiers, MEA, cooling system and measurement ports.

The polarization curves show the expected PEMFC behaviour: cell voltage decreased as current density increased, reflecting activation losses at low current density, ohmic losses at intermediate current density and mass-transport limitations at high current density. The 40 and 50 °C cases represent sub-optimal cold-operation conditions relative to the commonly used 60-80 °C PEMFC range. Their inclusion is useful because it demonstrates the performance penalty before the stack reaches its normal thermal window. The 40 °C case gave the weakest high-current response because lower temperature reduces electrode-reaction rates and membrane proton conductivity. Increasing the inlet temperature improved the high-current region as oxygen-reduction kinetics and proton transport became more favourable.

The 70 °C case provided the best high-current tolerance, with a more gradual voltage decline and the broadest power-density region. This result is consistent with improved catalyst-layer reaction kinetics and lower effective electrochemical losses at 70 °C compared with the lower-temperature cases; it should not be interpreted as evidence that catalyst activity alone determines the optimum. The 60 °C case also showed substantially better behaviour than 40 and 50 °C and remained within the conventional PEMFC operating range. Thus, the useful range is 60-70 °C rather than a single optimum point. The upper end provides stronger power response, whereas the lower end offers a larger thermal and hydration safety margin.

3. Results and Discussion

3.1 Polarization and power-density response

The polarization curves show the expected PEMFC behaviour: cell voltage decreased as current density increased. This trend reflects the transition from activation losses at low current density to ohmic losses at intermediate current density and mass-transport limitations at high current density. The 40 °C case gave the weakest high-current response because lower temperature reduces reaction kinetics and increases the effective resistance associated with proton transport. Increasing the inlet temperature improved the high-current region because the electrochemical reactions became more favourable and membrane conductivity was enhanced.

The 70 °C case provided the best high-current tolerance, with a more gradual voltage decline and the broadest power-density region. The 60 °C case also showed improved behaviour compared with 40 and 50 °C, suggesting that the useful temperature window is not a single point but a range. The important engineering implication is that operating at 60-70 °C can improve the available current and power under dynamic demand, but the upper part of this range requires strict humidification and cooling control to avoid dehydration.

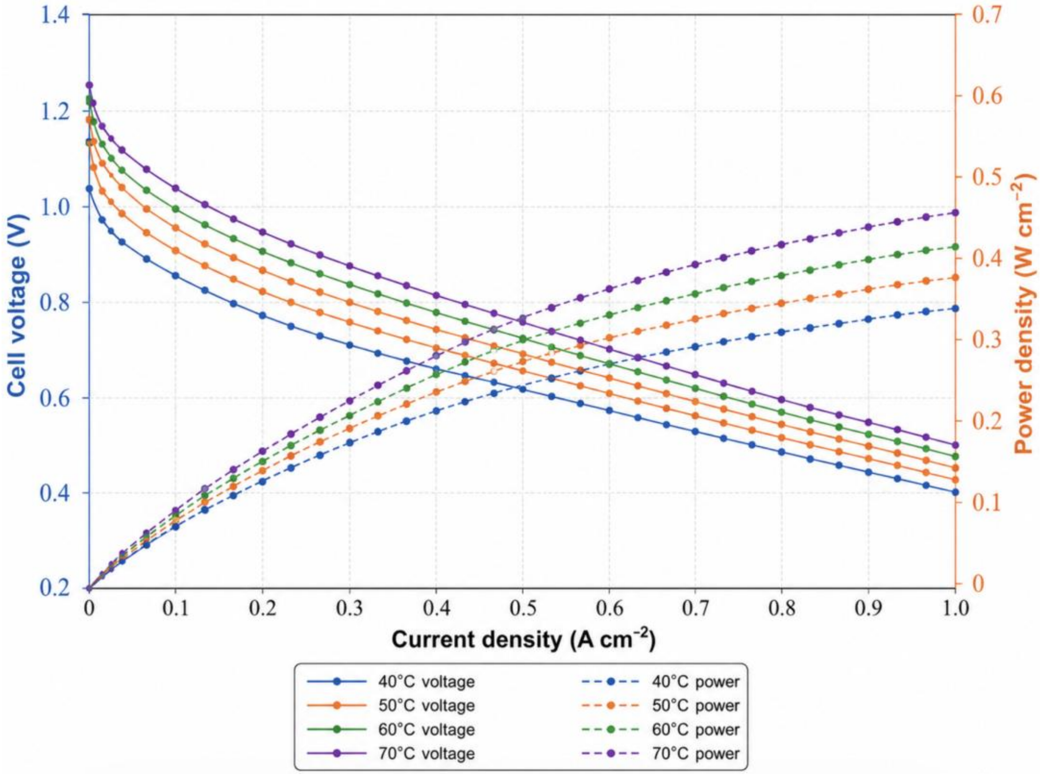

Figure 2. Comparative I-V and power-density behaviour for inlet temperatures of 40, 50, 60 and 70 °C.

A limitation of this temperature comparison is that the model uses lumped stack temperature and prescribed component parameters. It therefore cannot resolve local hot spots, cell-to-cell temperature variation, membrane dry-out fronts or spatial water accumulation. Consequently, the predicted 364 K peak should be interpreted as a system-level warning indicator rather than a local maximum temperature for every cell.

Table 2. Condensed comparison of key performance indicators from the dynamic PEMFC simulations.

Metric	40 °C	50 °C	60 °C	70 °C
Polarization response	Lowest high-current tolerance	Moderate improvement	Better voltage retention	Best high-current response
Steady stack temperature	353 K	353 K	353 K	353 K
Peak stack temperature	353 K	355 K	357 K	364 K
Dynamic current-density peak	~0.95 A cm-2	~0.95 A cm-2	~0.95 A cm-2	~0.95 A cm-2
Heat-generation peak	37-40 kW range	37-40 kW range	37-40 kW range	37-40 kW range
Water-production peak	Up to ~10 g s-1	Up to ~10 g s-1	Up to ~10 g s-1	Up to ~10 g s-1

Hydrogen-consumption peak	Up to ~1.1 g s-1	Up to ~1.1 g s-1	Up to ~1.1 g s-1	Up to ~1.1 g s-1
Overall interpretation	Stable but lower performance	Intermediate	Recommended balance	Highest output but highest thermal risk

3.2 Dynamic temperature behaviour

The stack temperature increased rapidly from the inlet value during the early transient period because PEMFC reactions are exothermic and internal losses produce heat. The temperature response generally reached a quasi-steady level after approximately 300-500 s, followed by small oscillations associated with load variation and thermal dynamics. The important finding is that all inlet-temperature cases converged to a steady stack temperature of approximately 353 K, equivalent to about 80 °C. This indicates that the cooling system and stack thermal mass drove the system toward a similar nominal operating temperature.

However, the peak temperature increased systematically with inlet temperature. The 40 °C case peaked at 353 K, whereas the 70 °C case reached 364 K. This 11 K increase is important because PEMFC membranes and catalyst layers are sensitive to hydration loss and thermal degradation. While higher temperature improves kinetics, the observed peak at 70 °C indicates that cooling-system capacity and humidifier control must be designed for transient peaks rather than only steady-state temperature.

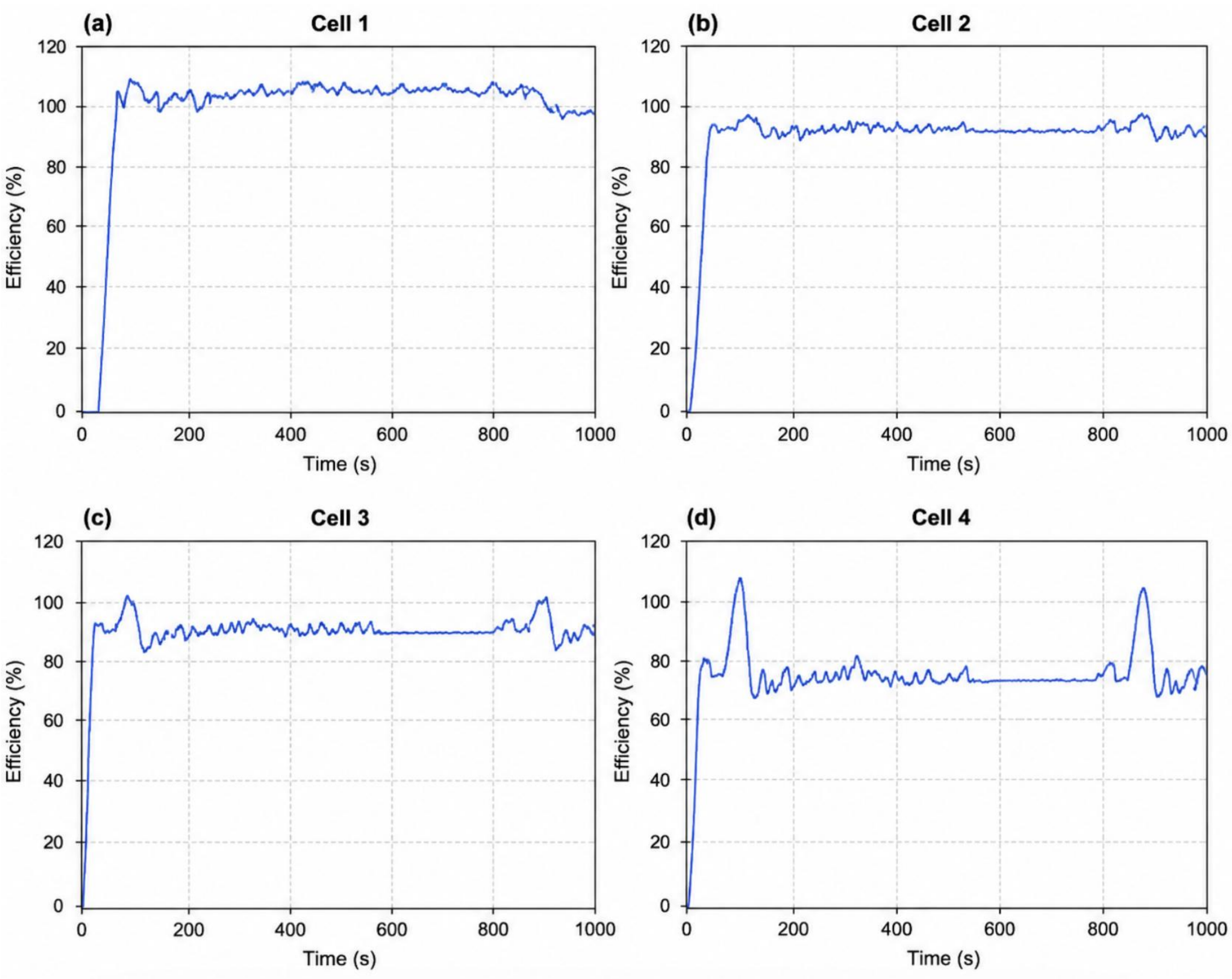

Figure 3. Dynamic stack-temperature response for all inlet-temperature cases. The stack approaches approximately 353 K, but peak temperature increases with inlet temperature.

3.3 Current density, voltage stability and load-following capability

The dynamic current-density response was strongly shaped by the imposed load profile. All temperature cases showed transient peaks and oscillations, with current density reaching approximately 0.95 A cm-2 during high-demand periods. The similarity of current-density peaks across the temperature range indicates that the load profile, rather than inlet temperature alone, dominated the instantaneous current demand. Nevertheless, the associated voltage response improved slightly at higher temperature, especially under high-current conditions, because activation and ohmic losses were reduced.

Stack voltage oscillated with the dynamic load. It started at higher values during low-current operation and decreased when the current demand increased. This behaviour is consistent with PEMFC loss mechanisms. The higher-temperature cases showed better average voltage stability, indicating that elevated temperature can improve load-following capability. For practical systems, this result supports the use of temperature-informed control strategies that coordinate stack temperature, humidification and cooling to reduce voltage drops during load transients.

3.4 Heat generation and electrical power output

Heat generation is a critical design parameter because it determines the required cooling capacity and influences membrane hydration. In the simulations, heat generation varied dynamically with current and voltage. Heat peaks occurred during high-current periods, when activation, ohmic and concentration losses were most severe. Across the four inlet-temperature cases, the peak heat generation was approximately 37-40 kW, whereas the heat value approached a low level during low-load or resting intervals. This confirms that the cooling system must be sized for peak transient heat removal, not merely average operating heat.

The electrical power output followed the same dynamic pattern as the current and voltage response. The higher-temperature cases, particularly 60 and 70 °C, showed slightly more stable power delivery. The 70 °C case provided the strongest output tendency because improved kinetics reduced internal losses. However, the higher peak stack temperature at 70 °C also introduces greater risk of membrane dehydration. Therefore, the 70 °C case is best interpreted as a high-performance operating point that requires robust thermal and water control, while 60 °C may represent a safer compromise between performance and durability.

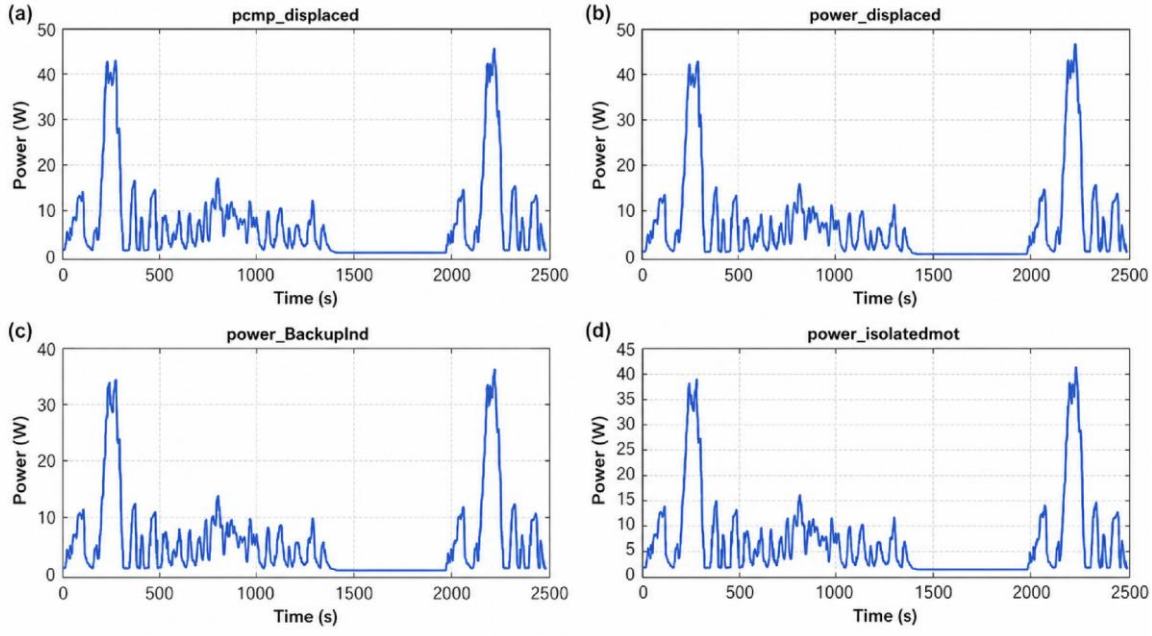

Figure 4. Dynamic heat-generation response for all inlet-temperature cases. Peak heat generation of approximately 37-40 kW indicates the cooling requirement during load transients.

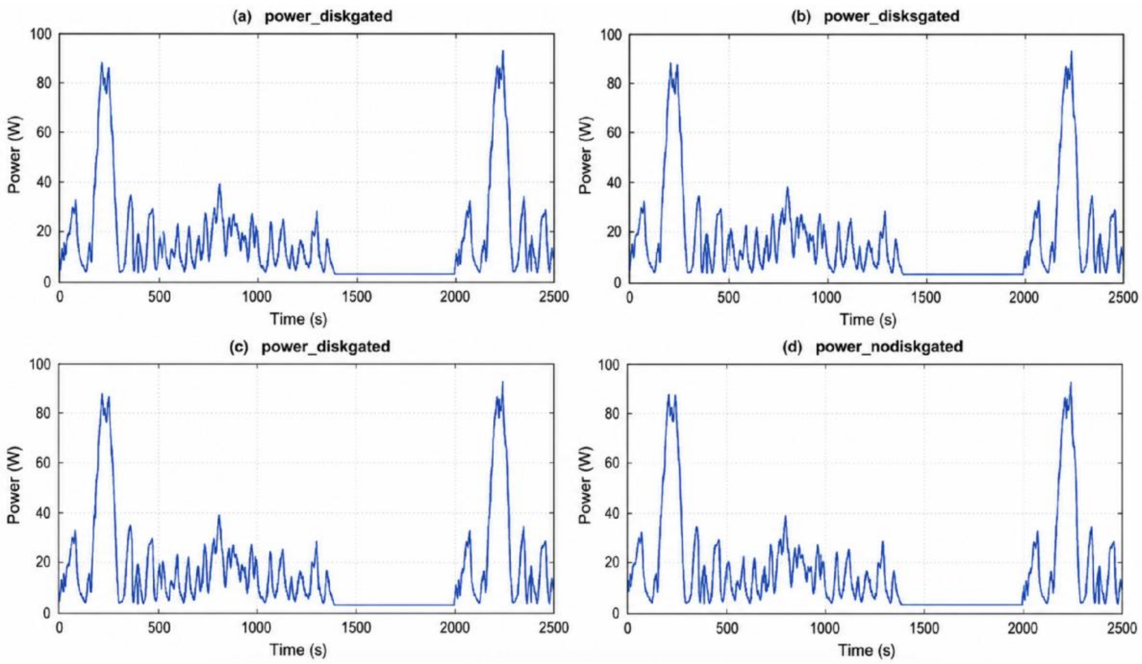

Figure 5. Dynamic PEMFC stack power output under the same load profile. Higher-temperature cases show slightly improved stability and output response.

3.5 Water production and hydrogen consumption

Water production is both a useful indicator of electrochemical activity and a potential source of performance loss. In the simulations, water production followed the load profile and increased during high-current operation. Peak water production reached approximately 10 g s-1, while low-load periods approached 0-4 g s-1. This confirms correct coupling between electrochemical reaction rate, current generation and product-water formation. From a design perspective, the result emphasises that water management must be dynamic. Excessive water accumulation can flood electrodes and reduce oxygen access, while insufficient water leads to membrane dehydration and higher ohmic losses.

Hydrogen consumption also followed the current and power demand. The average consumption reached up to approximately 0.4 g s-1 during nominal operation, while peak consumption reached approximately 1.1 g s-1. This value is important for hydrogen supply sizing, pressure regulation and purge strategy. A supply system designed only around average consumption could experience pressure drop during peak demand. Higher temperature may reduce some voltage losses and improve reaction kinetics, but it does not remove the need for adequate fuel delivery during transients. Therefore, stack control should coordinate temperature, reactant flow and water management rather than optimising temperature alone.

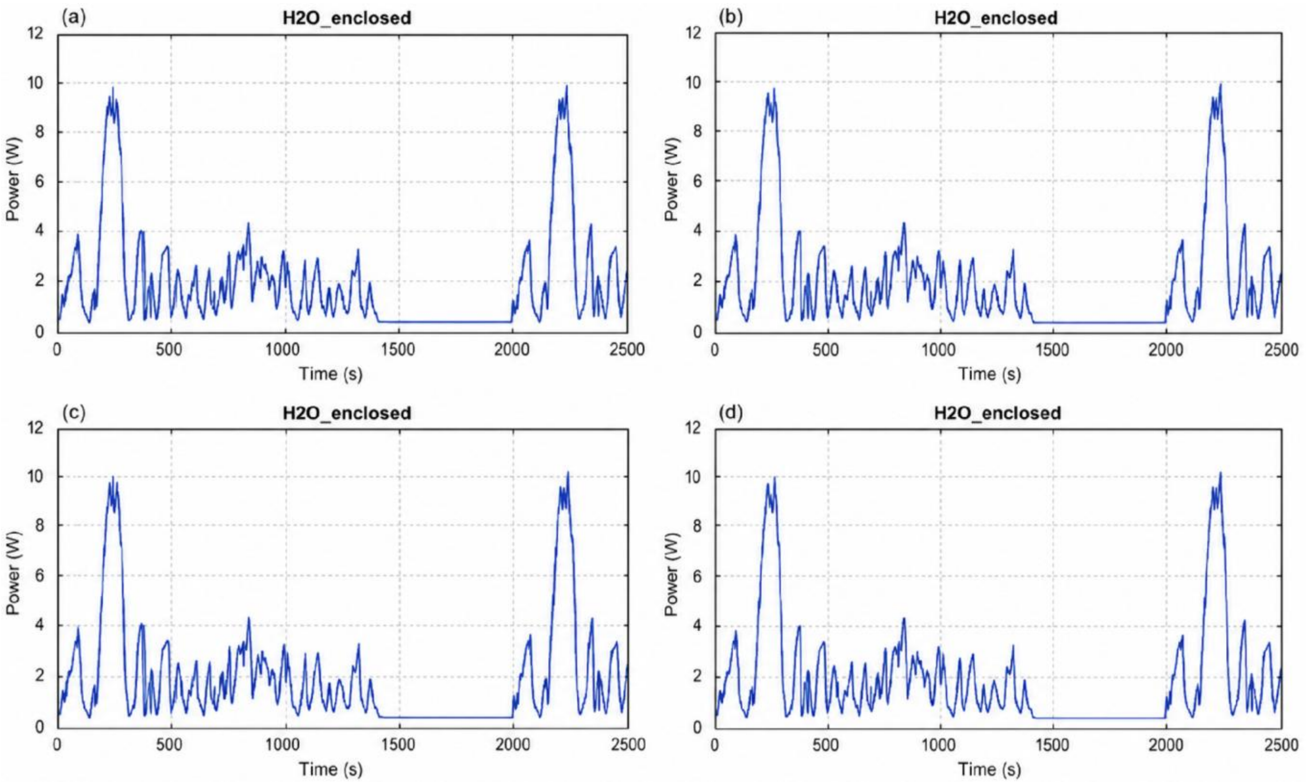

Figure 6. Water-production response under dynamic load. Product-water formation follows the current and power profile, with peaks of about 10 g s^{-1}.

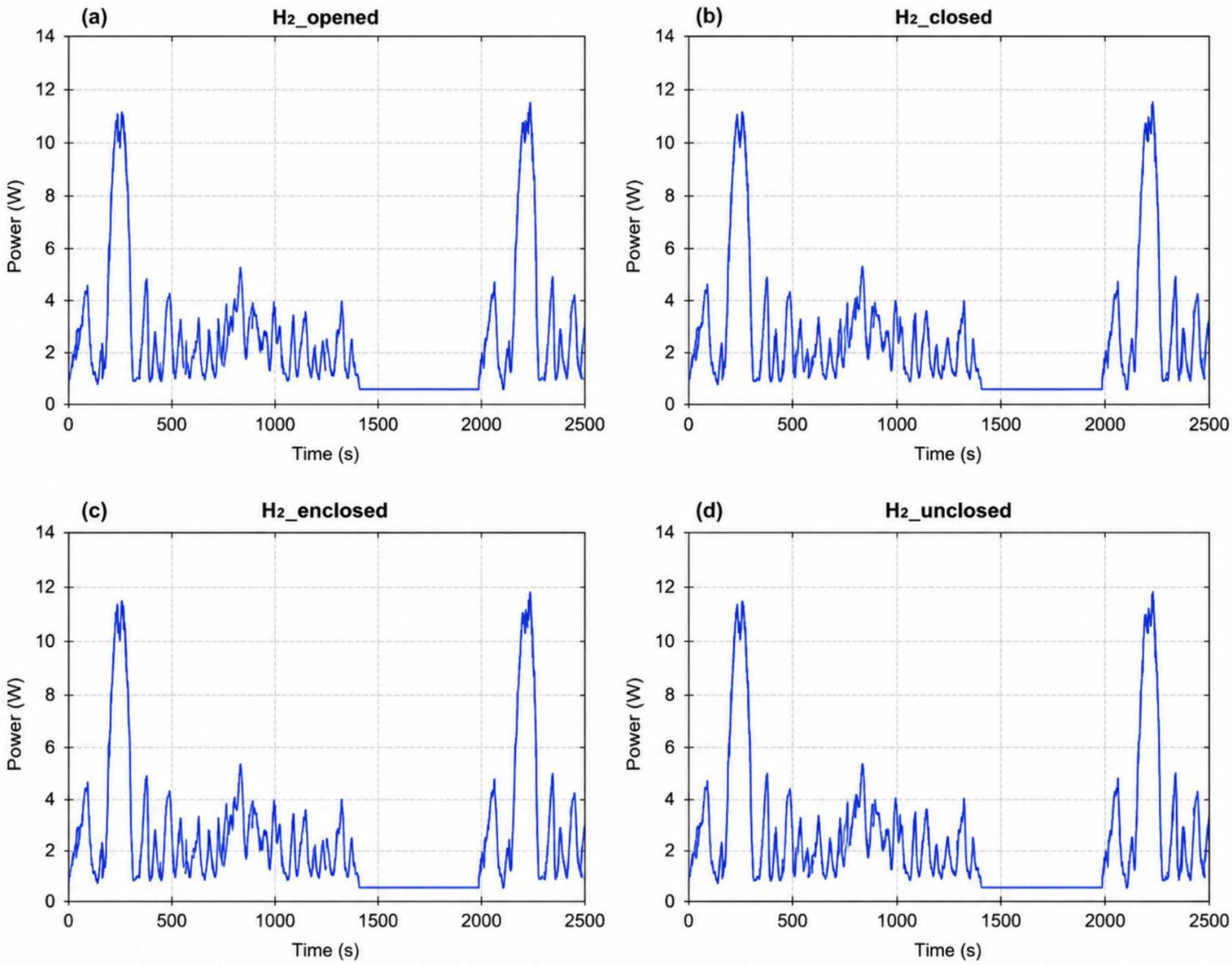

Figure 7. Hydrogen-consumption response under dynamic load. Peak hydrogen demand of about 1.1 g s-1 should be considered in fuel-supply sizing.

4. Practical Operating-Window Assessment

The combined results indicate that the PEMFC stack benefits from elevated inlet temperature, especially when high-current operation is required. The 40 °C case is thermally safer but provides weaker polarization behaviour. The 50 °C case improves performance but remains intermediate. The 60 °C case gives a favourable balance between improved kinetics, acceptable peak temperature and manageable water/thermal loads. The 70 °C case provides the strongest high-current and power response, but also produces the highest peak stack temperature and therefore the highest dehydration risk.

The operating-window recommendation is subject to several model limitations. Long-term catalyst ageing, membrane chemical degradation, mechanical stress, manufacturing variability, sensor uncertainty and cell-to-cell maldistribution are not represented explicitly. In addition, the hydrogen pressure and balance-of-plant parameters are model inputs rather than experimentally calibrated values for a specific physical stack. These omissions do not invalidate the comparative temperature trend, but they limit the use of the present results for absolute component sizing or lifetime prediction.

For an energy-system application, the recommended operating window is therefore 60-70 °C, with 60 °C as the more conservative set point and 70 °C as a high-performance set point requiring stronger cooling and humidification. The exact choice should depend on the application priority. If maximum transient power is required and the balance-of-plant can remove heat effectively, 70 °C is attractive. If durability and control margin are more important, 60 °C is preferable. In both cases, water and thermal management must be designed as active control functions rather than passive supporting components.

5. Conclusions

A MATLAB-Simscape PEMFC model was used to evaluate the effect of inlet temperature on a 400-cell stack under dynamic load. Relative to the thesis, the journal study applies a controlled four-temperature comparison, integrates electrochemical and balance-of-plant outputs, and introduces an operating-window interpretation supported by physical-consistency and literature-based trend checks. Increasing inlet temperature from 40 to 70 °C improved high-current polarization behaviour and power stability. All cases approached a quasi-steady stack temperature of approximately 353 K, but peak stack temperature increased from 353 K at 40 °C to 364 K at 70 °C. Current density reached approximately 0.95 A cm-2, heat generation peaked at about 37-40 kW, water production reached about 10 g s-1 and hydrogen consumption reached about 1.1 g s-1 during peak demand.

The main conclusion is that 60-70 °C is the most useful inlet-temperature range for the simulated system. The 70 °C case gives the strongest high-current response because electrochemical kinetics are more favourable, whereas 60 °C provides a more conservative compromise with greater thermal and hydration margin. The recommendation remains conditional because the model has not yet been validated against matched experimental data. Future work should therefore compare the simulation with polarization curves, electrochemical impedance spectra, distributed stack-temperature measurements, hydrogen-flow data and water-balance measurements obtained under the same transient load cycle. Subsequent model development should incorporate spatial temperature and hydration effects, degradation submodels and closed-loop control of cooling, humidification and hydrogen delivery. Until such validation is completed, the present model is most appropriate for comparative trend analysis and preliminary operating-window screening rather than absolute performance certification.

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Author Contributions

The authors declare that they contributed equally to all stages of this manuscript and research.

Declaration of Competing Interest

The authors declare no conflict of interest.

Data availability

The simulation data were generated from the MATLAB-Simscape model described in this manuscript and can be made available upon reasonable request.

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