

Research Paper

Effect of Operating Conditions on Proton Exchange Membrane Fuel Cell Performance: A One-Dimensional Mathematical Model Applied to an Electric Motorcycle

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🌐 <https://doi.org/10.31603/ae.16149>

Published by Automotive Laboratory of Universitas Muhammadiyah Magelang

Article Info

Submitted:

06/02/2026

Revised:

22/06/2026

Accepted:

13/07/2026

Online first:

21/07/2026

Abstract

The performance of a proton exchange membrane fuel cell (PEMFC) is strongly influenced by its operating conditions. In this study, a one-dimensional (1-D) mathematical model is developed to investigate PEMFC performance while explicitly accounting for water transport within the fuel cell during operation. The results demonstrate that the cell output performance is significantly affected by key operating parameters, including operating temperature, operating pressure, membrane thickness, exchange current density, and charge transfer coefficient. In addition, gas species transport and water management are incorporated into the model. The developed model is further applied to evaluate and analyze the dynamic performance characteristics of a hydrogen fuel cell electric motorcycle, including hydrogen consumption, water generation, and energy efficiency under the World Motorcycle Test Cycle (WMTC). This study provides a meaningful framework for predicting and designing the dynamic performance of hydrogen fuel cell electric motorcycles under realistic operating conditions.

Keywords: Proton exchange membrane fuel cell; Water transport in PEMFC; Water molar fraction; Driving cycle test; Hydrogen fuel cell electric motorcycle; Electric motorcycle dynamic

1. Introduction

Proton exchange membrane fuel cells (PEMFCs) are considered a promising energy power source for future applications due to their advantageous characteristics, including high energy efficiency, high power density, relatively low operating temperature, rapid start-up capability, and zero emissions [1]. In recent years, PEMFCs have been widely applied across a broad range of applications, such as portable power systems [2], [3], stationary power sources [4], [5], automobiles [6], [7], tramway [8], [9], unmanned underwater vehicles (UUVs) [10], unmanned aerospace vehicles (UAVs) [11], and ships [12].

The output performance of a proton exchange membrane fuel cell (PEMFC) is strongly influenced by operating conditions, including

operating temperature, operating pressure, humidity, stoichiometric ratio, and physical parameters. Numerous studies have investigated these effects. Askaripour *et al.* [13] analyzed the influence of operating conditions on PEMFC performance using a two-phase flow model and reported that increasing humidity led to only a slight improvement in cell performance, whereas higher operating temperatures significantly enhanced performance. Kanani *et al.* [14] developed a model based on response surface methodology to evaluate the effects of operating conditions on PEMFC output voltage and optimized parameters such as relative humidity, anode stoichiometry, and cathode stoichiometry. Santarelli *et al.* [15] experimentally investigated the impact of operating conditions on PEMFC performance and found that increasing both



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humidity and operating pressure substantially improved cell performance. Jang *et al.* [16] evaluated individual cell performance under different operating conditions and observed that cell performance in the center region improved with increased humidity and temperature.

Kaytakoğlu *et al.* [17] optimized PEMFC performance using the Taguchi method and reported that the optimal performance occurred at an operating pressure of 5 bar and an operating temperature of 75 °C. Pan *et al.* [18] studied the effects of operating conditions on PEMFC performance using different flow field designs, including serpentine, parallel, and pin-type channels, and concluded that transport–reaction interactions dominate PEMFC performance. Similarly, Yan *et al.* [19] experimentally investigated cell voltage under various operating conditions and five different flow field types, demonstrating that the parallel flow field achieved the highest performance. Yan *et al.* [20] further compared conventional and interdigitated flow fields and reported a 66.67% performance improvement with the interdigitated design. Liu *et al.* [21] optimized flow field channels under varying operating conditions and showed that tapered channels outperform conventional designs due to enhanced gas transport and improved electrochemical reaction participation. Xie *et al.* [22] applied an orthogonal experimental approach and found that increasing operating pressure from 1 MPa to 3 MPa improved power density by 11.2%. Ozen *et al.* [23] investigated the effects of operating temperature and humidity and reported improved performance with increased inlet gas humidification and temperature.

Amirinejad evaluated PEMFC output voltage under different operating temperatures, pressures, and humidity levels, concluding that higher pressure and gas humidification enhance cell performance [24]. Zhu *et al.* [25] studied the influence of operating conditions on PEMFC performance uniformity and reported power density improvements ranging from 4.78% to 15.44%, along with performance uniformity enhancements between 29.95% and 66.94%. Yan *et al.* [26] examined PEMFC performance under steady-state and dynamic conditions and found that optimal performance occurred at operating temperatures between 65 and 75 °C and pressures

from 1 to 4 atm. Coppo *et al.* [27] reported that higher operating temperatures improve PEMFC performance due to increased electrical conductivity. Chu *et al.* [28] investigated fuel cell durability under dynamic loading over 1000 h and observed that high potentials significantly accelerate catalyst layer degradation. Similarly, Ohyagi *et al.* [29] reported a 50% catalyst layer degradation rate under a humidity of 187%. Li *et al.* [30] studied membrane electrode assembly (MEA) characteristics under varying operating conditions and concluded that thinner membranes reduce ohmic losses and facilitate membrane hydration. Lim *et al.* [31] evaluated PEMFC performance under effective operating conditions and found that increased humidity and temperature accelerate catalyst layer corrosion. Tohidi *et al.* [32] investigated primary operating parameters and showed that performance improves with increasing pressure and temperature but declines with higher inlet humidity and membrane thickness. Shan *et al.* [33] modeled PEMFC performance at different operating temperatures and demonstrated that higher temperatures enhance output performance due to improved electrical conductivity.

Peng *et al.* [34] applied a support vector machine (SVM) to determine optimal PEMFC operating conditions, identifying an operating temperature of 86.2 K, electrical conductivity of 997.7 S/m, cathode humidity of 64.4%, and operating pressure of 3.44 atm, achieving a maximum power density of 870 mW cm⁻². Tan *et al.* [35] optimized PEMFC systems using neural networks and particle swarm optimization (PSO), achieving increases of 1.33% in power density and 12.8% in system efficiency. Zhang *et al.* [36] experimentally investigated the effects of relative humidity and operating temperature and found that cell performance declined as humidity decreased from 100% to 25%. Xiao *et al.* [37] studied external operating conditions under membrane drying and reported increased charge transfer impedance with greater drying severity. Yang *et al.* [38] investigated the combined effects of operating conditions and load modes and identified optimal operating conditions at 65 °C, with anode and cathode humidity ratios of 70 °C and 60 °C, respectively. Verma *et al.* [39] analyzed the influence of operating conditions on PEMFC transient response, focusing on anode and

cathode parameters. Wei *et al.* [40] examined water accumulation in the gas diffusion layer and found that higher humidity promotes water transport toward the anode. Ge *et al.* [41] investigated the effect of gas diffusion layer compression and reported improved performance with increasing compression up to an optimal point, beyond which performance declined. Misran *et al.* [42] studied water transport characteristics under various temperatures and pressures and concluded that relative humidity plays a dominant role. Zhao *et al.* [43] analyzed temperature distribution in an open-cathode PEMFC under different operating conditions and found that temperature non-uniformity increases with higher operating current density.

Recently, hydrogen fuel cell technology has been increasingly deployed in electric motorcycles. Weigl *et al.* [44] designed and tested a hydrogen fuel cell electric motorcycle and subsequently optimized its energy efficiency. Di Giorgio *et al.* [45] experimentally investigated thermal management in a fuel cell–battery hybrid system and proposed an improved method for battery pack thermal regulation. Handa *et al.* [46] developed a hydrogen fuel cell–powered electric motorcycle and demonstrated that this configuration can be implemented using existing hydrogen refueling infrastructure. Unal *et al.* [47] developed a hydrogen fuel cell model for an electric motorcycle and reported that the power output of the hydrogen fuel cell electric motorcycle was more than 120% higher than that of a battery electric motorcycle. Lin *et al.* [48] designed and modeled a hydrogen fuel cell power system for an electric motorcycle, showing that a transient power demand of 5.9 kW during rapid acceleration requires a hydrogen system with a volume of 43 L and a mass of 46 kg. Shih *et al.* [49] experimentally evaluated the performance of a hydrogen fuel cell–battery hybrid electric motorcycle and reported a maximum speed of 53.2 km h⁻¹ and a refueling range of 63.5 km. Kumari *et al.* [50] optimized a fuel cell–battery hybrid system for an electric motorcycle and validated its performance through road tests, achieving a driving range of 100 km with a hydrogen consumption of 50 g. Wang *et al.* [51] investigated energy management strategies for fuel cell hybrid electric motorcycles using fuzzy logic control and demonstrated a 16% reduction in

hydrogen consumption. Hsu *et al.* [52] designed and implemented a hydrogen fuel cell–battery hybrid electric motorcycle and reported a significant reduction in air pollutant emissions when this configuration was deployed.

In summary, PEMFC performance is significantly influenced by operating conditions. The one-dimensional (1-D) modeling approach provides a powerful and computationally efficient tool compared with more complex numerical methods. Although the PEMFC performance has been developed with 1-D modeling methods, but still limited and almost focused on under steady-state conditions. In this study, a 1-D mathematical model is developed to simulate and analyze PEMFC performance, with particular emphasis on predicting water transport within the fuel cell, which is challenging to quantify experimentally. The model is validated through comparison with previously published results under steady-state conditions. Furthermore, the validated model is applied to a hydrogen fuel cell electric motorcycle to evaluate its dynamic performance under a driving cycle test. Key performance indicators, including stack voltage, water generation, hydrogen consumption, and energy efficiency, are analyzed in detail. Overall, this study contributes to reducing computational cost while maintaining predictive accuracy for PEMFC performance evaluation and system-level applications. Additionally, the application of hydrogen energy to the electric motorcycle contributed to toward net zero emissions by 2050.

2. Method

2.1. PEMFC Model Description

2.1.1. PEMFC operation review

Figure 1a illustrates the operating principle of the PEMFC. Hydrogen and oxygen (or air) are supplied to the anode and cathode, respectively. Electrochemical reactions occur within the fuel cell, involving oxidation at the anode and reduction at the cathode, as described by Eqs. (1) – (3). These electrochemical reactions generate electrical energy, along with heat and water as byproducts. Figure 1b presents an exploded view of the PEMFC components. The components of the PEMFC and their corresponding functions are summarized in Table 1. These components are described from the central region to the outermost layers of the fuel cell.

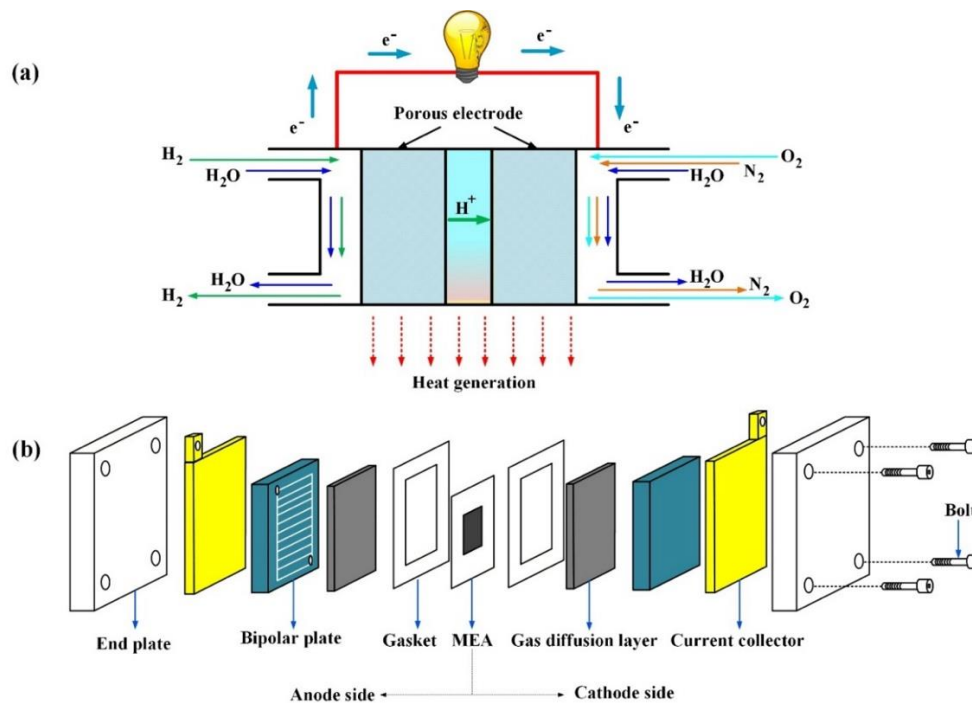


Figure 1. (a) PEMFC principle; (b) Exploded view of PEMFC components

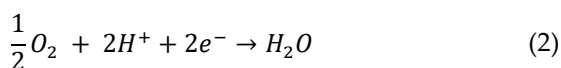
Table 1. The components of the PEMFC description

Component	Function
Membrane electrode assembly (MEA)	It consisted of the membrane and catalytic layer. The anode and cathode catalyst layers were loaded with the ink.
Gasket	It was employed to prevent a gas leak. It is usually made of plastic material to fabricate it.
Gas diffusion layer (GDL)	This component was used to protect the catalyst layer and keep the water vapor to prevent membrane dehydration during fuel cell operation.
Bibolar plate	It was applied to conduct the gas through the flow field channels and conduct the electricity flow to the outside. Additionally, this place contains the water accumulation from the electrochemical reaction.
Current collector	The current collector collects the current and conducts the electrical energy to the outside.
End plate	It is the cover role, also called the housing.
Bolts	Bolts were used to hold the PEMFC components.

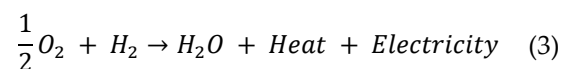
Oxidation:



Reduction:



Overall:



2.1.2. One-dimensional (1-D) description and boundary conditions

The one-dimensional (1-D) model is a powerful tool for predicting PEMFC performance while significantly reducing computational cost.

In this study, the 1-D model is applied to simulate and analyze cell performance using the MATLAB software environment. **Figure 2** illustrates the PEMFC operating principle and the transport of gas species within the fuel cell. It can be observed that water is transported from the anode to the cathode via electro-osmotic drag, which is induced by proton transport toward the cathode. In addition, water at the cathode side diffuses back to the anode due to the back-diffusion phenomenon.

In this study, the 1-D model is developed with consideration of the z-axis that represents the flux of gas species within the fuel cell. The Eq. (4) presents the flux of gas species.

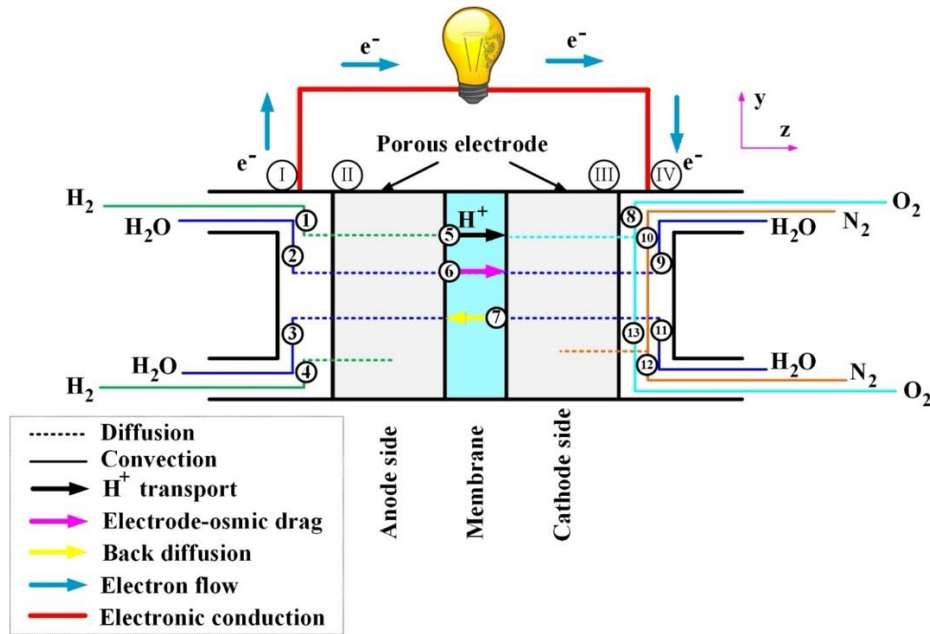


Figure 2. Gas species transport in PEMFC model

$$\frac{i}{2F} = \frac{n_{H^+}}{2} = n_{H_2}^A = 2n_{O_2}^C = s_{H_2O}^C \quad (4)$$

where, i is the operating current density, in $A\ cm^{-2}$; F represents the Faraday's constant ($F = 96485\ C\ mol^{-1}$); n_{H^+} is the molar flux of the hydrogen proton through the membrane, in $mol\ s^{-1}$; $n_{H_2}^A$ denotes the molar flux of the hydrogen at the anode side, in $mol\ s^{-1}$; $n_{O_2}^C$ refers to the molar flux of the oxygen gas at the cathode side, in $mol\ s^{-1}$; and $s_{H_2O}^C$ represents the water generation rate per cell activation area, in $mol\ m^{-2}\ s^{-1}$.

The molar flux of the hydrogen gas at the anode side and the molar flux of the oxygen gas at the cathode side were calculated following Eqs. (5) and (6), respectively:

$$n_{H_2}^A = \frac{N_{H_2,1} - N_{H_2,4}}{A_{cell}} \quad (5)$$

$$n_{O_2}^C = \frac{N_{O_2,8} - N_{O_2,13}}{A_{cell}} \quad (6)$$

During the PEMFC operation, water is transported within the fuel cell, encompassing the water transport from the anode to the cathode side due to the electrode osmotic drag phenomenon, water transport from the cathode to the anode side

owing to the back diffusion phenomenon, and water generation from the electrochemical reaction and accumulated at the cathode side. According to the water balance principle, the relationship between water rate can be determined by Eq. (7); where, $N_{H_2O,i}$ represents the molar flow rate of water at the position i .

The water flux at the anode, membrane, and cathode side were balanced, as follows Eq. (8); where, $n_{H_2O}^A$, $n_{H_2O}^{mem}$, and $n_{H_2O}^C$ denote the net water flux at the anode, membrane, and cathode side. Additionally, the water flux was defined at the membrane, as follows Eq. (9); where, α represents the water flux ratio coefficient in the membrane. Consequently, the water flux at the cathode side was determined by Eq. (10). By combining with Eq. (4), the final balance flux was expressed as follows Eq. (11).

Although the mathematical model was developed in this study, the assumptions were provided to ensure consistency and appropriate ideal operating conditions during the PEMFC operation. To simplify and facilitate the development of the one-dimensional (1-D) PEMFC mathematical model in this study, the following assumptions are made:

$$N_{H_2O,2} - N_{H_2O,3} = N_{H_2O,6} - N_{H_2O,7} = N_{H_2O,12} - N_{H_2O,9} - N_{H_2O,5} \quad (7)$$

$$n_{H_2O}^A = n_{H_2O}^{mem} = n_{H_2O}^C - \frac{i}{2F} \quad (8)$$

$$n_{H_2O}^{mem} = \alpha \frac{i}{2F} \quad (9)$$

$$n_{H_2O}^c = (\alpha + 1) \frac{i}{2F} \quad (10)$$

$$\frac{i}{2F} = \frac{n_{H^+}}{2} = n_{H_2}^A = 2n_{O_2}^c = \frac{n_{H_2O}^A}{\alpha} = \frac{n_{H_2O}^{mem}}{\alpha} = \frac{n_{H_2O}^c}{\alpha + 1} \quad (11)$$

- The operating pressure is identical throughout all flow field channels, which neglects local pressure drops and flow maldistribution, which may occur in practical fuel cell stacks, particularly at high current densities or under transient operating conditions.
- The operating temperature is uniform across the fuel cell, which ignores temperature gradients caused by non-uniform heat generation and cooling, which can affect reaction kinetics, membrane hydration, and overall cell performance.
- The catalyst layer loading at both the anode and cathode is uniformly distributed over the active area, which does not account for manufacturing variations, catalyst degradation, or localized aging effects that may influence electrochemical activity.
- No liquid water is present in the flow field channels prior to fuel cell operation. Before the operation simplifies the water management analysis, but it may not accurately represent startup conditions, humid environments, or residual water accumulation from previous operating cycles.
- Cell potentials are uniformly distributed over the active area, disregarding local voltage variations caused by reactant concentration gradients, current density non-uniformity, and contact resistance effects.

2.1.3. Cell output voltage

During the PEMFC operation, the cell output voltage can be determined by Eq. (12). It includes the reversible voltage and irreversible voltage. The irreversible represents the summation of cell voltage loss.

$$V_{cell} = V_{rev} - V_{irev} \quad (12)$$

where, V_{rev} and V_{irev} denote the reversible voltage and irreversible voltage of the PEMFC, respectively. All parameters are in units of V.

The reversible voltage of PEMFC represents the maximum output voltage of the cell without the voltage loss. At the standard conditions with an operating pressure of 1 atm, and an operating temperature of 25 °C, the reversible was calculated by Eq. (13), as follows:

$$V_{rev} = \frac{-\Delta G}{nF} = 1.229 \text{ V} \quad (13)$$

where, ΔG is the Gibbs free energy owing to the electrochemical reaction ($G = -237340$), in J mol⁻¹; n denotes the electron exchange number ($n = 2$); and F refers to Faraday's constant ($F = 96485$), in C mol⁻¹.

In practice, the PEMFC operated under different operating conditions. Therefore, the cell's reversible voltage was affected by the operating temperature and pressure. In this context, it was determined by Eq. (14); where, T_{cell} represents the operating temperature, in K; P_{H_2} refers to the anode pressure, in kPa; and P_{O_2} denotes the cathode pressure, in kPa.

The irreversible voltage consisted of the summation of cell activation voltage loss, ohmic voltage loss, and concentration voltage loss. Eq. (15) expressed the irreversible voltage for the cell PEMFC; where, V_{act} , V_{ohm} , and V_{conc} denotes the activation voltage loss, ohmic voltage loss, and concentration voltage loss, respectively. All values are in units of V.

2.1.4. Activation voltage loss

The operating current density can be determined following the Butler-Volmer Eq. (16); where, i_0 represents the exchange current density, in A cm⁻²; $\alpha_{Rec,c}$ is the charge transfer coefficient in the reduction process; E_c refers to the reversible voltage, in V; $E_{r,c}$ is the cathode potential, in V; $\alpha_{Ox,c}$ denotes the charge transfer coefficient in the oxidation process, and R refers to the ideal gas constant ($R = 8.314 \text{ J mol}^{-1}$).

The exchange current density can be determined by Eq. (17).

$$V_{rev} = 1.229 - 0.85 \times 10^{-3}(T_{cell} - 298.15) + 4.3085 \times 10^{-5}T_{cell} \left[\ln \left(\frac{P_{H_2}}{101325} \right) + \frac{1}{2} \ln \left(\frac{P_{O_2}}{101325} \right) \right] \quad (14)$$

$$V_{irev} = V_{act} + V_{ohm} + V_{conc} \quad (15)$$

$$i = i_0 \left\{ \exp \left[-\frac{\alpha_{Rec,c} F (E_c - E_{r,c})}{RT_{cell}} \right] - \exp \left[-\frac{\alpha_{Ox,c} F (E_c - E_{r,c})}{RT_{cell}} \right] \right\} \quad (16)$$

$$i_0 = i_{0,ref} \left(\frac{C_{O_2}}{C_{O_2,ref}} \right) \quad (17)$$

where, $i_{0,ref}$, C_{O_2} , and $C_{O_2,ref}$ represent the reference exchange current density, oxygen molar concentration, and reference oxygen molar concentration, respectively. The oxygen molar concentration and reference oxygen molar concentration were determined, corresponding to Eqs. (18) and (19).

$$C_{O_2} = \frac{X_{O_2} P^c \times 101325}{RT_{cell}} \quad (18)$$

$$C_{O_2,ref} = \frac{1 \times 101325}{RT_{cell}} \quad (19)$$

where, X_{O_2} is the molar fraction of the oxygen, and P^c denotes the cathode pressure, in atm.

Therefore, Eq. (16) becomes the new form as following Eq. (20). By assuming that the cell activation voltage loss at the cathode $V_{act,c} = E_c - E_{r,c}$ is not too small, the relation can be arranged as Eq. (21).

From the Eq. (21), the Eq. (22) can be obtained after extracting the Eq. (21). In Eq. (22), $X_{O_2}^{III}$ is the molar fraction of oxygen on the catalytic layer, as shown in region III. The oxygen flux at the cathode side can be determined by Eq. (23); where, D_{O_2,H_2O}^{eff} represents the effective binary diffusion coefficient of oxygen and water vapor, and z is the direction of the membrane. By solving the above differential equation of Eq. (23), the molar fraction of oxygen was obtained as follows Eq. (24).

$$i = i_{0,ref} \left(\frac{C_{O_2}}{C_{O_2,ref}} \right) \left\{ \exp \left[-\frac{\alpha_{Rec,c} F (E_c - E_{r,c})}{RT_{cell}} \right] - \exp \left[-\frac{\alpha_{Ox,c} F (E_c - E_{r,c})}{RT_{cell}} \right] \right\} \quad (20)$$

$$i = i_{0,ref} \left(\frac{C_{O_2}}{C_{O_2,ref}} \right) \exp \left[\frac{\alpha_{Rec,c} F V_{act,c}}{RT_{cell}} \right] \quad (21)$$

$$V_{act} = \frac{RT_{cell}}{\alpha_{Rec,c} F} \ln \left[\frac{i}{i_{0,ref}} \times \frac{101325}{P^c X_{O_2}^{III}} \right] \quad (22)$$

By choosing z as the cathode catalytic layer (t^c), the molar fraction of oxygen at region III can be expressed in Eq. (25). By substituting Eq. (25) into Eq. (22), the cell cathode activation voltage loss was obtained as Eq. (26).

2.1.5. Ohmic voltage loss

The ohmic voltage loss represents the voltage drop associated with the ionic resistance of the membrane. Determining the ohmic loss is not straightforward because it is strongly influenced by water transport within the fuel cell, including electro-osmotic drag and back-diffusion phenomena. The water flux through the membrane can be determined using Eq. (27); where, c_{drag}^{SAT} represents the drag coefficient at the saturated condition ($c_{drag}^{SAT} = 2.5$); λ denotes the water content in the membrane; $\rho_{dry,mem}$ is the Nafion density at the dry condition; M_{Nafion} refers to the equivalent weight of the Nafion; and $D_{H_2O,Nafion}$ is the diffusion coefficient of the water in the Nafion.

The diffusion coefficient of the water in the Nafion, in $m^2 s^{-1}$, can be calculated by Eq. (28). The water content in the membrane is a function of the membrane direction (z). It was determined based on the thickness of the membrane with $z = 0$ and $z = t_{mem}$. It can be expressed as follows Eq. (29). There are two unknown variables in this equation, α and κ . The water content in the membrane was defined by Eq. (30); where, a_w represents the water activity. It was determined based on the boundary condition of the membrane thickness.

$$n_{O_2}^c = -\frac{P^c D_{O_2, H_2O}^{eff}}{RT_{cell}} \frac{dX_{O_2}}{dz} \quad (23)$$

$$X_{O_2}(z) = X_{O_2}^{IV} - \frac{RT_{cell} n_{O_2}^c}{P^c D_{O_2, H_2O}^{eff}} \quad (24)$$

$$X_{O_2}^{III} = X_{O_2}^{IV} - \frac{RT_{cell} n_{O_2}^c}{P^c D_{O_2, H_2O}^{eff}} t^c = X_{O_2}^{IV} - \frac{RT_{cell}}{4F P^c D_{O_2, H_2O}^{eff}} t^c \quad (25)$$

$$V_{act} = \frac{RT_{cell}}{\alpha_{Rec,c} F} \left[\ln \left(\frac{i}{i_{0,ref}} \right) - \ln \left(\frac{P^c}{101325} \left\{ X_{O_2}^{IV} - \frac{RT_{cell}}{4F P^c D_{O_2, H_2O}^{eff}} t^c \right\} \right) \right] \quad (26)$$

$$n_{H_2O}^{mem} = c_{drag}^{SAT} \frac{\lambda}{22 F} - \frac{\rho_{dry,mem}}{M_{Nafion}} D_{H_2O, Nafion} \frac{d\lambda}{dz} = \frac{\alpha i}{2F} \quad (27)$$

$$D_{H_2O, Nafion} = \frac{1}{14 - 4} \int_4^{14} \left\{ \exp \left[2416 \left(\frac{1}{303} - \frac{1}{T_{cell}} \right) \right] \times (2.563 - 0.33\lambda + 0.0264\lambda^2 - 0.000671\lambda^3) \times 10^{-10} d\lambda \right\} = 1.3113 \times 10^{-10} \exp \left[2416 \left(\frac{1}{303} - \frac{1}{T_{cell}} \right) \right] \quad (28)$$

$$\lambda(z) = \frac{11\alpha}{c_{drag}^{SAT}} + \kappa \exp \left[\frac{i \times c_{drag}^{SAT} M_{Nafion}}{22F \rho_{dry,mem} 1.3113 \times 10^{-10} \exp \left[2416 \left(\frac{1}{303} - \frac{1}{T_{cell}} \right) \right]} z \right] \quad (29)$$

$$\lambda = \begin{cases} 0.043 + 17.18a_w - 39.85a_w^2 + 36a_w^3, & 0 < a_w < 1 \\ 14 + 4(a_w - 1), & 1 \leq a_w < 3 \end{cases} \quad (30)$$

$$a_w|_{z=0} = \frac{P_w|_{z=0}}{P_{sat}} = \frac{P^A X_{H_2O}^{II}}{P_{sat}} \quad (31)$$

$$a_w|_{z=t_{mem}} = \frac{P_w|_{z=t_{mem}}}{P_{sat}} = \frac{P^A X_{H_2O}^{III}}{P_{sat}} \quad (32)$$

The electrical conductivity of the Nafion can be determined by Eq. (33). It depends on the membrane thickness and operating temperature of the fuel cell. The ohmic voltage loss was calculated by Eq. (34).

2.1.6. Concentration voltage loss

The concentration voltage loss occurred when the fuel cell was operating at a high load level. It can be determined by Eq. (35) and can be rearranged following the Eq. (36) model. The molar fraction of the water in region III can be calculated by Eq. (37). The molar fraction of the water and the molar fraction of the hydrogen in region II can be calculated by Eq. (38) and Eq. (39); where, t^A is the anode membrane thickness, in m.

2.1.7. Stack voltage and stack power

In practice, the single cell PEMFC is connected in a series configuration to achieve the high voltage, which is called the fuel cell stack configuration. The output voltage of the fuel cell stack and stack power were determined by Eq. (41) and (42), respectively; where, N_{cell} and I_{stack} represent the number of cells in a stack, and the operating current of the fuel cell, in A.

2.1.8. Mathematical model of an electric motorcycle dynamic

In this study, the PEMFC model is employed to design and evaluate the performance of an electric motorcycle after modeling and simulation of the fuel cell power source. The developed model is then integrated into the electric motorcycle system. **Figure 3** illustrates the dynamic performance of the electric motorcycle, which consists of the traction force and the various resistance forces acting during vehicle operation.

$$\sigma(z, T_{cell}) = (0.5193\lambda(z) - 0.326) \left[1268 \left(\frac{1}{303} - \frac{1}{T_{cell}} \right) \right] \quad (33)$$

$$V_{ohm} = i \times A_{cell} \times R_{mem} = i \int_0^{t_{mem}} \frac{dz}{\sigma(z, T_{cell})} \quad (34)$$

$$V_{conc} = E_c - E_{c,ref} = \left\{ E_{rev,c} - \frac{RT_{cell}}{2F} \ln \frac{P_{O_2}^{0.5}}{P_{H_2O}} \right\} - \left\{ E_{rev,c} - \frac{RT_{cell}}{2F} \ln \frac{P_{O_2}^{0.5}}{P_{H_2O}} \right\}_{ref} \quad (35)$$

$$V_{conc} = \frac{RT_{cell}}{2F} \ln \left[\left(\frac{X_{O_2}^{IV}}{X_{O_2}^{III}} \right)^{0.5} \left(\frac{X_{H_2O}^{III}}{X_{H_2O}^{IV}} \right) \right] \quad (36)$$

$$X_{H_2O}^{III} = X_{H_2O}^{IV} + \frac{RT_{cell}i(\alpha+1)/2F}{P^C D_{O_2, H_2O}^{eff}} t^C \quad (37)$$

$$X_{H_2O}^{II} = X_{H_2O}^I - \frac{RT_{cell}i\alpha/2F}{P^A D_{O_2, H_2O}^{eff}} t^A \quad (38)$$

$$X_{H_2}^{II} = X_{H_2}^I - \frac{RT_{cell}i\alpha/2F}{P^A D_{O_2, H_2O}^{eff}} t^A \quad (39)$$

$$V_{conc} = \frac{RT_{cell}}{2F} \ln \left[\left(\frac{X_{O_2}^{IV}}{X_{H_2O}^{IV} + \frac{RT_{cell}i(\alpha+1)/2F}{P^C D_{O_2, H_2O}^{eff}} t^C} \right)^{0.5} \left(\frac{X_{H_2O}^{IV} + \frac{RT_{cell}i(\alpha+1)/2F}{P^C D_{O_2, H_2O}^{eff}} t^C}{X_{H_2O}^{IV}} \right) \right] \quad (40)$$

$$V_{stack} = N_{cell} V_{cell} \quad (41)$$

$$P_{stack} = N_{cell} V_{stack} I_{stack} = N_{cell} V_{cell} I_{stack} \quad (42)$$

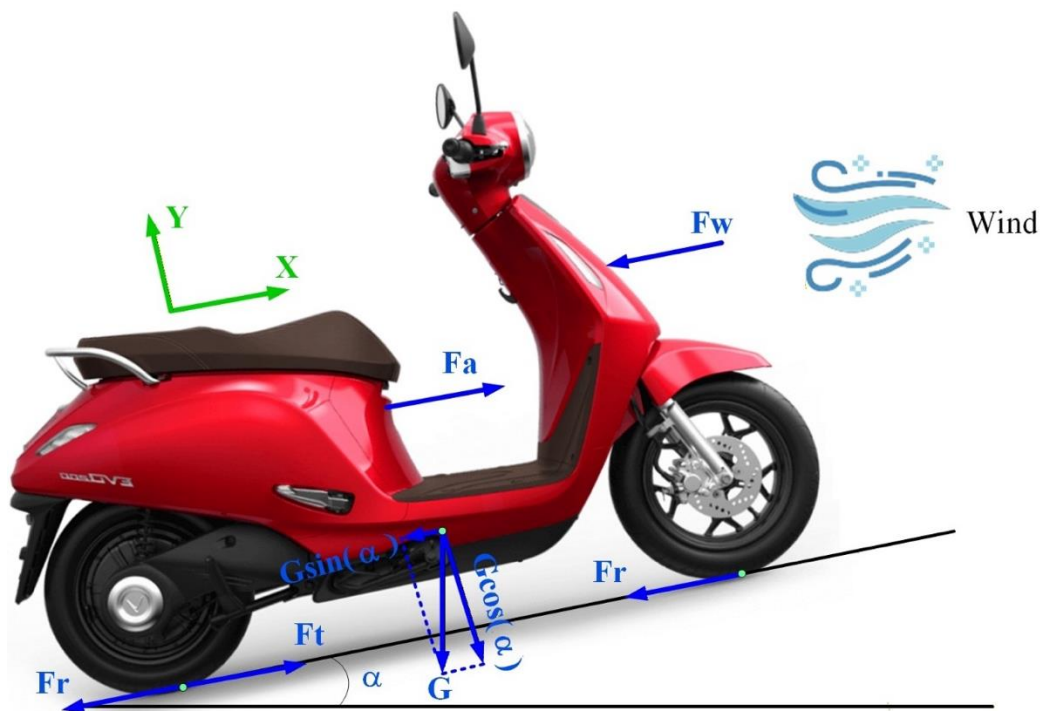


Figure 3. Hydrogen fuel cell electric motorcycle dynamic performance in the longitudinal plane

To facilitate and simplify the model, the following assumptions are made:

- The wheels of the electric motorcycle roll without slipping on the road surface during operation.
- The electric motorcycle operates in a straight line without cornering.
- Lateral resistance forces are neglected during longitudinal operation.
- The rolling resistance coefficient of the electric motorcycle is assumed to be constant.
- Wind is assumed to act only on the frontal area of the electric motorcycle.
- Fuel cell stack degradation is neglected during electric motorcycle operation.

Applying the Newton II law, the balanced forces of an electric motorcycle following the longitudinal direction were presented by Eq. (43).

$$F_t = F_r + F_w + F_c + F_a \quad (43)$$

where, F_t , F_r , F_w , F_c , and F_a denotes the traction force, rolling resistance force, wind resistance force, slope climbing resistance force, and acceleration force, respectively.

The rolling resistance force, wind resistance force, slope climbing resistance force, and acceleration force were expressed, corresponding to Eqs. (44) to (47).

$$F_r = m_{EM} g \mu \cos(\alpha) \quad (44)$$

$$F_w = 0.5 A_{EM} \epsilon_d \rho_d V^2 \quad (45)$$

$$F_c = m_{EM} g \sin(\alpha) \quad (46)$$

$$F_a = m_{EM} \frac{dV}{dt} \quad (47)$$

where, m_{EM} represents the mass of an electric motorcycle, in kg; g is the gravitational acceleration, ($g = 9.81 \text{ m s}^{-2}$); μ denotes the rolling coefficient; α is the slope angle, in degree; A_{EM} refers to the frontal area of an electric motorcycle, in m^2 ; ϵ_d is the aerodynamic drag coefficient; ρ_d denotes the air density ($\rho_d = 1.25 \text{ kg m}^{-3}$); and V is the velocity of an electric motorcycle, in m s^{-1} .

The required power and torque of the fuel cell stack to supply the energy for an electric motorcycle can be determined, corresponding to Eq. (48) and Eq. (49):

$$P_t = K \frac{F_t V}{\eta_t \eta_e} \quad (48)$$

$$T_t = F_t R_{EM} \quad (49)$$

where, K denotes the safety coefficient during calculation and design of the required fuel cell power source, $K = 1.5$ is a fixed value in this study, to compensate for the degradation of the fuel cell power and auxiliary power consumption of an electric motorcycle, and ensure sufficient power supply for the propulsion system of an electric motorcycle. η_t is the transmission efficiency; η_e denotes the electrical efficiency; R_{EM} refers to the radius of the wheel, in m.

During the electric motorcycle operation, the load level is changed depending on the operating load of the electric motorcycle. Therefore, the operating current of the fuel cell stack can be expressed by Eq. (50).

$$I_m = \frac{P_t}{V_{stack}} \quad (50)$$

During the electric motorcycle operation, the electric motorcycle load level varied and depended on the operating conditions. Thus, determination of the gas consumption to manage and save it play critical. Indeed, the hydrogen gas consumption, in g s^{-1} , was calculated by Eq. (44).

$$\dot{m}_{H_2} = \frac{N_{cell} \times I_m}{2F} M_{H_2} \quad (51)$$

where, M_{H_2} denotes the molar mass of water, in g mol^{-1} .

Besides, the water generation of the fuel cell stack from the electrochemical reaction was calculated by Eq. (45) during an electric motorcycle operation on the road.

$$\dot{m}_{H_2O} = \frac{N_{cell} \times I_m}{4F} M_{H_2O} \quad (52)$$

where, M_{H_2O} represents the molar mass of water, in g mol^{-1} .

Ultimately, the energy efficiency of the fuel cell stack (EE) can be determined and expressed by Eq. (47).

$$EE = \frac{P_t}{I_m \times 1.25} 100 \quad (53)$$

2.1.9. Driving cycle test description

In this study, a driving cycle test is employed to evaluate the dynamic performance of the electric motorcycle. The electric motorcycle uses a hydrogen fuel cell as its power source, producing only water as a by-product. Therefore, the World

Motorcycle Test Cycle (WMTC) is adopted to assess the vehicle performance. The distance, velocity, and acceleration profile and key characteristics of the WMTC are illustrated in Figure 4 and summarized in Table 2.

2.1.10. Input parameter and solution procedure

Figure 5 illustrates the solution procedure of the one-dimensional (1-D) PEMFC model used in this study. The procedure includes the calculation of gas species molar fractions, as well as the determination of reversible and irreversible voltage losses. The input parameters used for modeling and simulation are summarized in Table 3.

After developing the one-dimensional (1-D) PEMFC mathematical model, the model is validated under various operating conditions. To further demonstrate the applicability of the proposed model, a hydrogen fuel cell electric motorcycle is employed to analyze and discuss its dynamic performance. The technical specifications of the hydrogen fuel cell electric motorcycle are listed in Table 4.

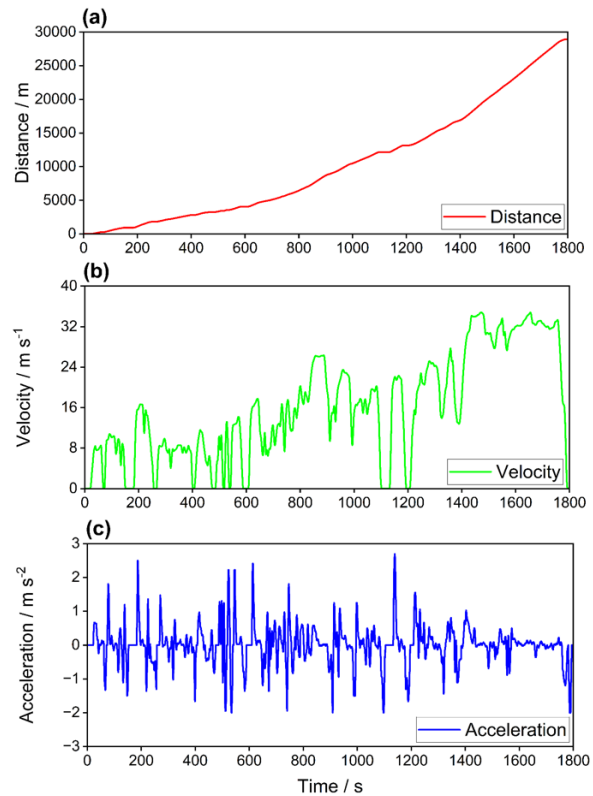


Figure 4. WMTC characteristics: (a) Distance; (b) Velocity; and (c) Acceleration

Table 2. WMTC key characteristics

Part	Conditions
WMTC part 1	This phase is used to evaluate the hydrogen fuel cell electric motorcycle under urban driving conditions (low speed, stop-and-go) from 0 to 600 s. The average and maximum velocities during this period are 6.78 and 16.67 m s ⁻¹ , respectively.
WMTC part 2	This phase is used to evaluate the hydrogen fuel cell electric motorcycle under rural and suburban regions from 600 to 1200 s. The average and maximum velocities during this period are 15.16 and 26.36 m s ⁻¹ , respectively.
WMTC part 3	This phase is used to evaluate the hydrogen fuel cell electric motorcycle under highway and extra-urban regions from 1200 to 1800 s. The average and maximum velocities during this period are 26.18 and 34.80 m s ⁻¹ , respectively.

Table 3. Input parameters to simulate and validate the PEMFC model in this study

Parameter	Symbol	Value	Unit
Operating current density	i	0 – 2.0	A cm ⁻²
Operating current temperature	T_{cell}	303 – 353	K
Cathode charge transfer coefficient	$\alpha_{Rec,c}$	2.0	–
Anode charge transfer coefficient	$\alpha_{Ox,a}$	2.0	–
Membrane thickness	t^{mem}	125	μm
Dry membrane density	$\rho_{dry,mem}$	0.00198	kg cm ⁻³
Equivalent weight of the membrane	M_{Nafion}	1.1	kg mol ⁻¹
Exchange current density	i_0	0.0001	A cm ⁻²
Effective hydrogen (or water) diffusion	D_{H_2,H_2O}^{eff}	1.49×10^{-5}	m ² s ⁻¹
Effective oxygen (or water) diffusion	D_{O_2,H_2O}^{eff}	2.95×10^{-6}	m ² s ⁻¹
Water diffusion coefficient	$D_{H_2O,Nafion}$	3.81×10^{-10}	m ² s ⁻¹
Anode catalyst layer thickness	t^A	450	μm
Cathode catalyst layer thickness	t^C	450	μm
Cell activation area	A_{cell}	25	cm ²
Anode operating pressure	p^A	1.5	atm
Cathode operating pressure	p^C	1.5	atm

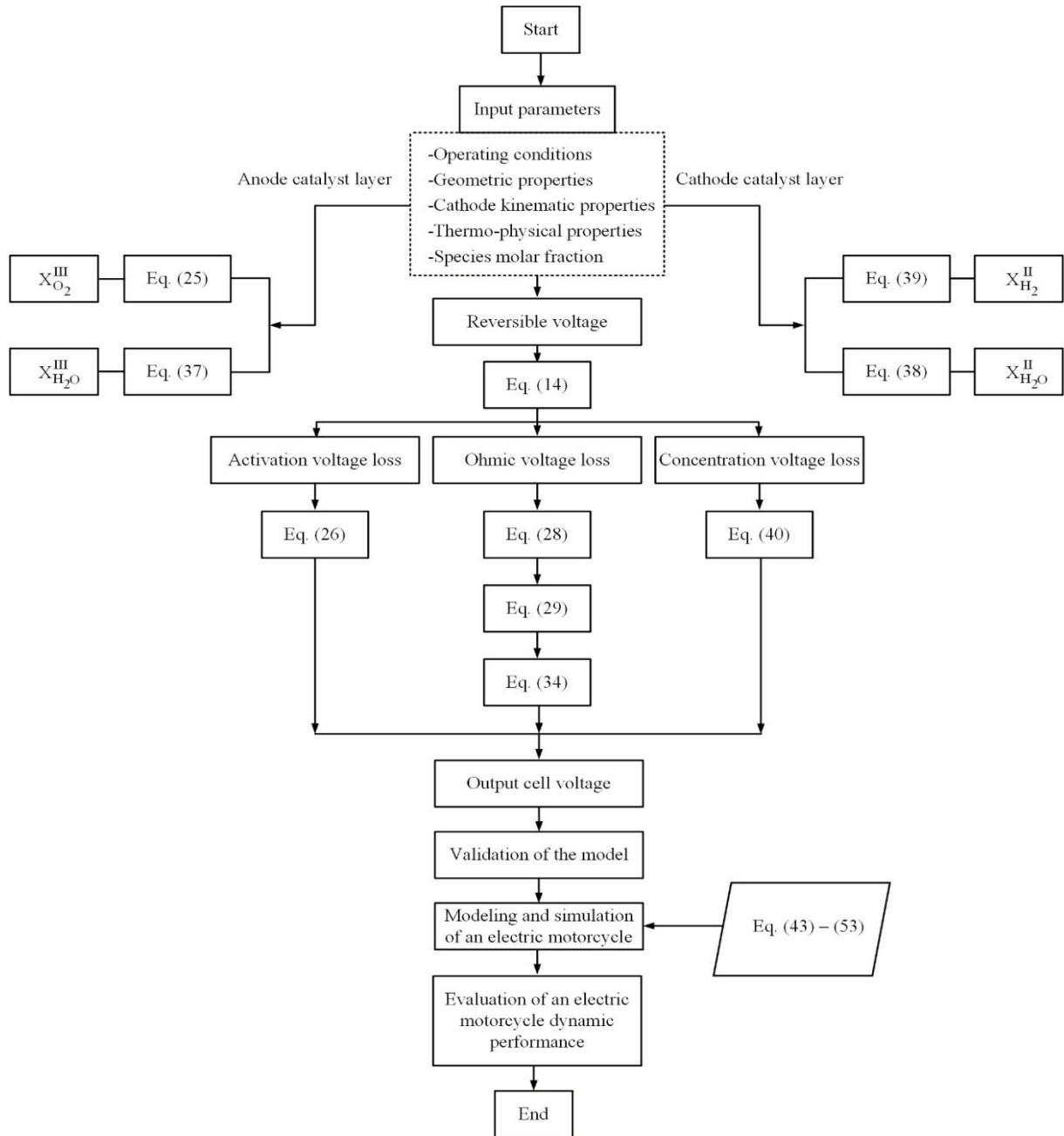


Figure 5. A 1-D model solution procedures

Table 4. Hydrogen fuel cell electric motorcycle technical specifications

Parameter	Symbol	Value	Unit
Frontal area of an electric motorcycle	A_{EM}	0.6	m ²
Radius of the wheel	R_{EM}	24	cm
Rolling resistance coefficient	μ	0.011	–
Aderodynamic drag coefficient	ϵ_d	0.6	–
Gravitational acceleration	g	9.81	m s ⁻²
Mass of the electric motorcycle	m_{EM}	130	kg
Mass of rider	m_{rider}	70	kg
Mass of passenger	m_{psg}	70	kg
Transmission efficiency	η_t	0.9	–
Electrical efficiency	η_e	0.95	–
Cell activation area	A_{cell}	25 × 25	cm ²
Number of cells	N_{cell}	60	cells
Rated output voltage source	V_{stack}	60	V

3. Results and Discussion

3.1. Model Validation

To verify the proposed model, the simulation results are validated and compared with previously published studies. **Figure 6** presents the PEMFC output cell voltage under different operating temperatures ranging from 50 to 90 °C. It can be observed that as the operating temperature increases, the cell performance improves due to enhanced electrical conductivity and accelerated electrochemical reaction kinetics within the fuel cell. In contrast, as the operating current density increases, the cell voltage decreases owing to increased overpotentials and water accumulation in the membrane, which reduces the effective active area of the cell. The resulting polarization curve trends are similar to those previously published results [15], [23], [27], [33], [53], [54], demonstrating the reliability of the proposed model.

3.2. Impact of Operating Temperature on PEMFC Performance

During fuel cell operation, the operating temperature has a significant influence on cell performance. **Figure 7** presents the output voltage and overpotential of a single PEMFC cell under different operating temperatures ranging from 50 to 90 °C, with increments of 10 °C.

The activation voltage loss increases with increasing operating current density and cell operating temperature; however, this increase is relatively small, as shown in **Figure 7a**. In contrast, the ohmic voltage loss increases significantly with operating current density, as illustrated in **Figure 7b**. It can also be observed that as the operating temperature increases, the ohmic voltage loss decreases. This behavior can be attributed to enhanced proton conductivity at higher temperatures, which reduces membrane resistance and, consequently, the ohmic overpotential.

The concentration voltage loss of the PEMFC is shown in **Figure 7c**. It can be observed that the concentration voltage loss increases with operating current density, as this loss becomes dominant at high load conditions due to limitations in mass transport during the electrochemical reactions. In general, the concentration voltage loss decreases with increasing operating temperature, owing to

improved gas diffusion and reduced concentration gradients at elevated temperatures. **Figure 7d** presents the polarization curves of the PEMFC under various operating current densities and temperatures, including both cell voltage and power density. As the operating current density increases, the output cell voltage decreases due to increased overpotentials within the fuel cell. Furthermore, increasing the operating temperature enhances cell performance as a result of accelerated electrochemical reaction kinetics and improved electrical conductivity. However, when the operating temperature exceeds 80 °C, cell performance begins to decline due to membrane dehydration. In this condition, reduced membrane hydration leads to lower proton conductivity and decreased cell efficiency. Therefore, the optimal operating temperature in this study is identified as 80 °C.

3.3. Impact of Operating Pressure on PEMFC Performance

The cell performance was investigated under various operating pressures at a fixed operating temperature of 60 °C. **Figure 8** illustrates the PEMFC output cell voltage under elevated anode and cathode pressures. It can be observed that increasing the operating pressure generally enhances cell performance due to improved reactant availability and reduced membrane resistance. However, at high operating current densities exceeding 1.5 A cm⁻², excessive water generation may block gas transport pathways and reduce the effective active area. Moreover, simultaneously increasing both anode and cathode

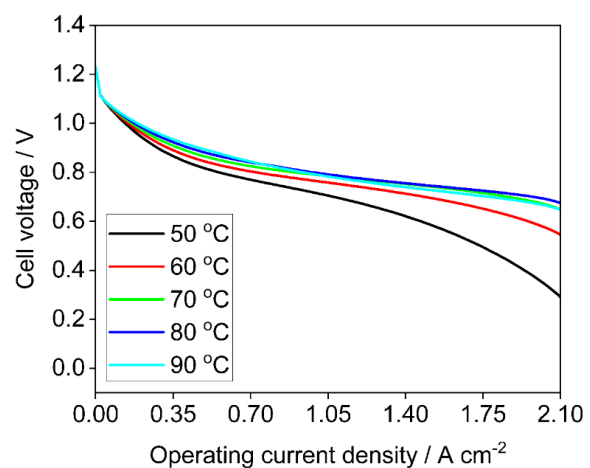


Figure 6. Cell performance under varying operating temperatures

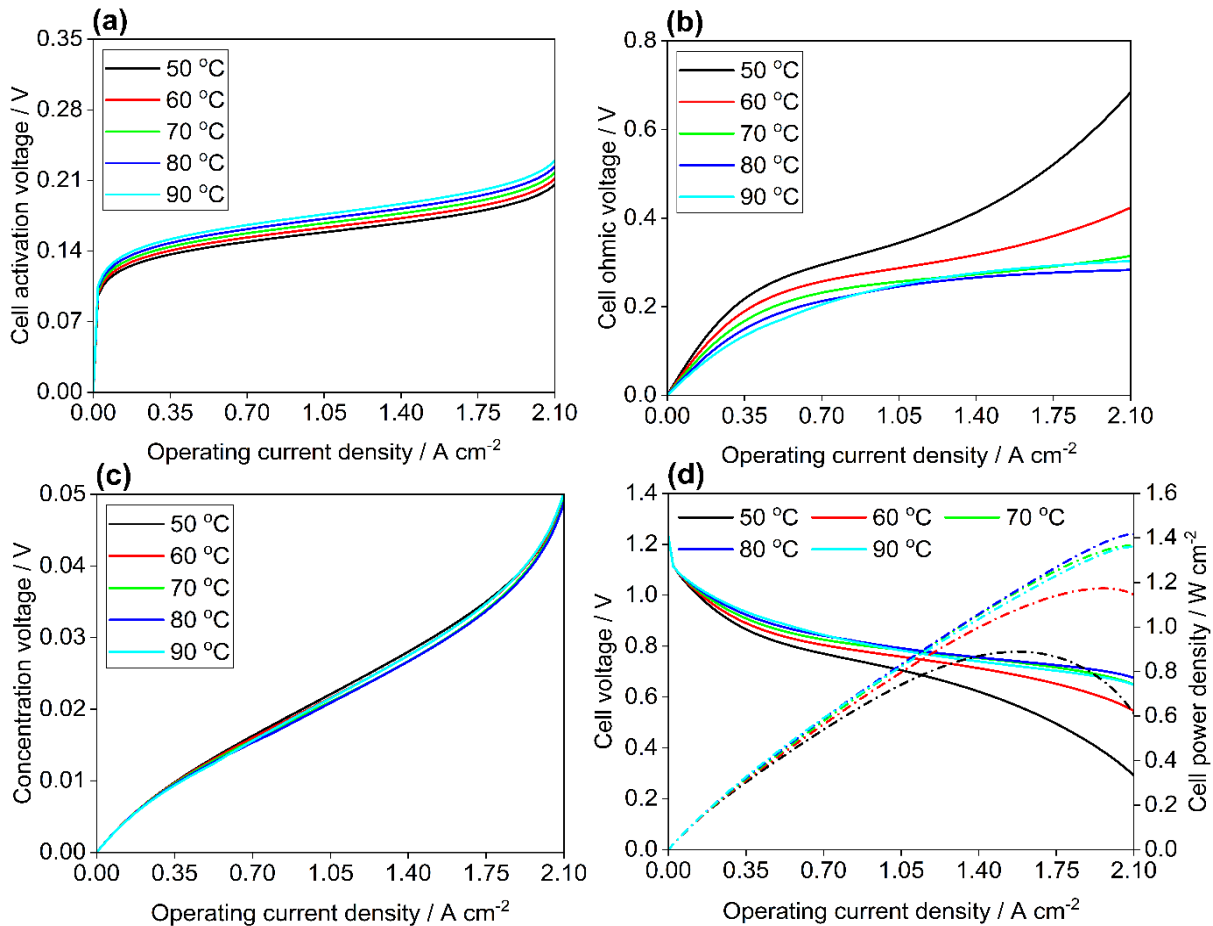


Figure 7. Cell performance under varying operating temperatures: (a) cell activation; (b) cell ohmic voltage; (c) cell concentration voltage; and (d) cell voltage and power density

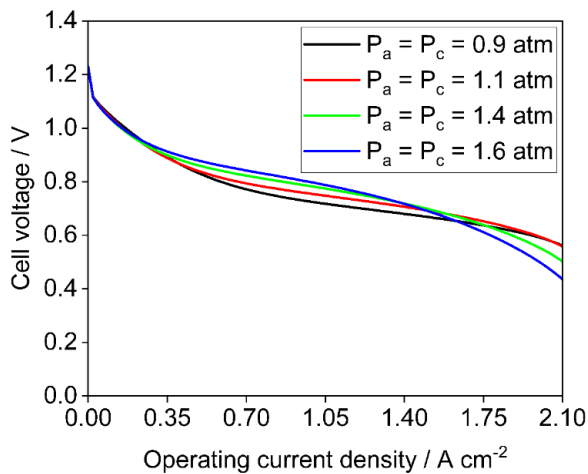


Figure 8. Cell performance under different pressures of both anode and cathode pressures

pressures can accelerate catalyst layer corrosion. Consequently, under high load conditions and elevated pressures, cell performance tends to decline rapidly. Overall, the optimal operating pressure in this study is identified as 1.2 atm, which represents a key operating parameter for PEMFC operation.

The effect of anode operating pressure was investigated over a range from 1.0 to 1.6 atm, with increments of 0.2 atm, as shown in [Figure 9](#). It is evident that increasing the anode operating pressure enhances cell performance. This improvement can be attributed to the increased hydrogen partial pressure, which promotes proton generation and transport, thereby enhancing the electrochemical reaction kinetics within the fuel cell.

To evaluate the effect of cathode operating pressure on cell performance, the cathode pressure was investigated over a range from 1.0 to 1.6 atm, with increments of 0.2 atm, as illustrated in [Figure 10](#). At low operating current densities, increasing the cathode operating pressure enhances cell performance. However, at higher operating current densities, further increases in cathode pressure lead to a decline in cell performance. This behavior can be explained by excessive water generation and accelerated catalyst layer corrosion at high pressures, which impede gas transport and reduce the effective electrochemically active area.

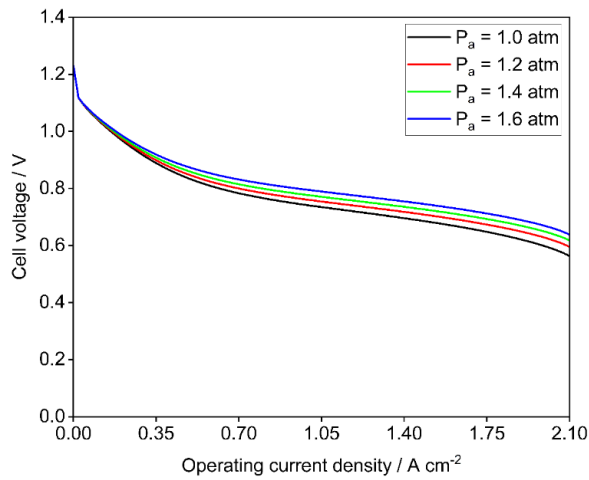


Figure 9. Cell performance under various anode operating pressures

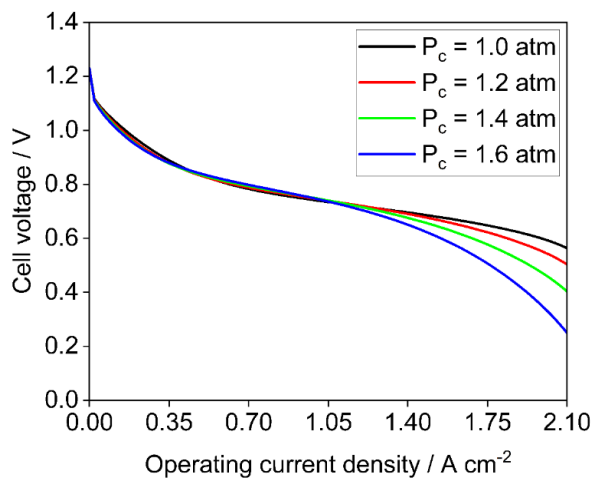


Figure 10. Cell performance under various cathode operating pressures

3.4. Impact of Catalyst Layer Thickness on PEMFC Performance

The fuel cell performance is influenced by the thickness of the catalyst layer during operation. In this section, the fuel cell is operated at an operating temperature of 60 °C, with both anode and cathode pressures set to 1.2 atm. **Figure 11** presents the output voltage of the fuel cell under varying catalyst layer thicknesses. It can be observed that increasing the catalyst layer thickness leads to an increase in cell voltage due to the higher catalyst loading, which enhances the electrochemical reaction rate.

Water transport within the fuel cell was considered in analyzing the effect of membrane thickness on cell performance. **Figure 12a** illustrates the water molar fraction at the anode under different catalyst layer thicknesses. It can be observed that as the catalyst layer thickness

increases, the water molar fraction at the anode side also increases. This behavior can be attributed to enhanced water retention and accumulation within the thicker catalyst layer. In contrast, the water molar fraction at the cathode side tends to decrease, as shown in **Figure 12b**. This occurs because the water concentration at the cathode is initially higher than that at the anode, creating a concentration gradient that drives water transport from the cathode to the anode. This transport mechanism is known as the back-diffusion phenomenon.

3.5. Impact of Reference Exchange Current Density on PEMFC Performance

During PEMFC operation, cell performance is significantly influenced by the reference exchange current density. **Figure 13** illustrates the relationship between operating current density and output cell voltage under different reference exchange current densities for a single cell. It can be observed that the cell voltage increases as the reference exchange current density increases. This behavior can be attributed to the enhancement of electrochemical reaction kinetics associated with a higher reference exchange current density, which reduces activation losses and consequently improves overall cell performance.

3.6. Impact of Transfer Coefficient on PEMFC Performance

The charge transfer coefficient has a notable influence on PEMFC performance. **Figure 14** presents the single-cell voltage under different values of the charge transfer coefficient. As the

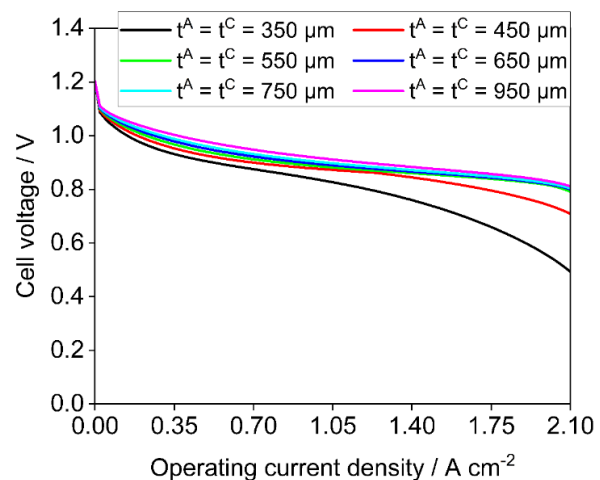


Figure 11. Cell performance under varying catalyst layer thickness

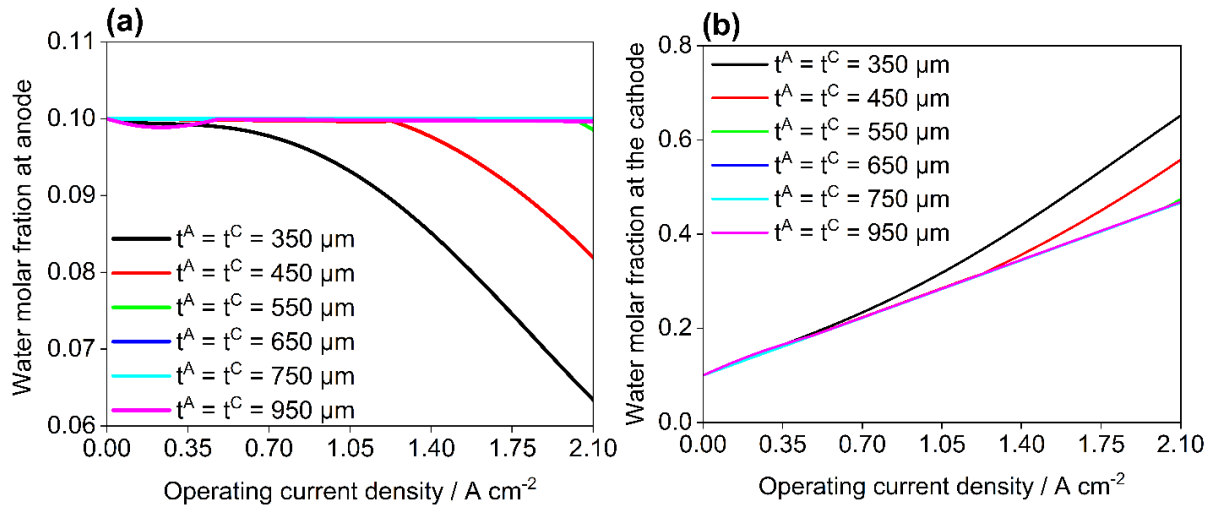


Figure 12. Water molar fraction under varying catalyst layer thickness: (a) Anode; and (b) Cathode

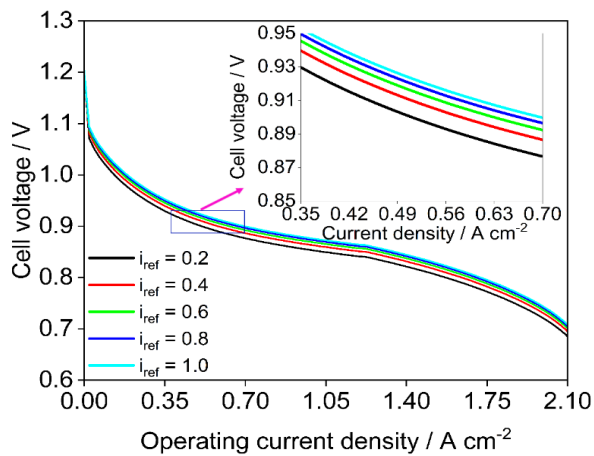


Figure 13. Cell performance under various reference exchange current densities

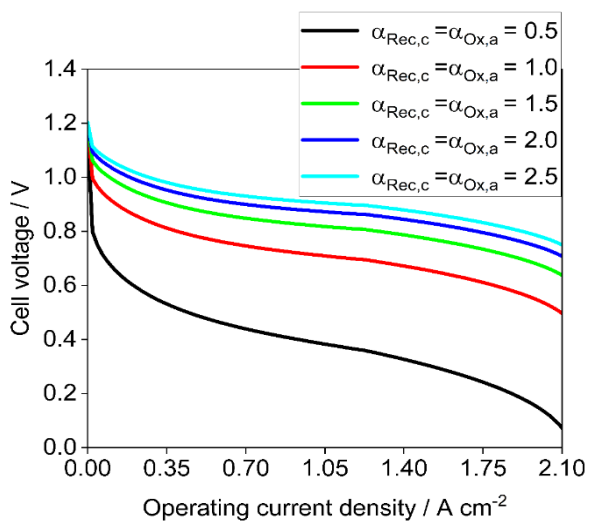


Figure 14. Effect of charge transfer on PEMFC

charge transfer coefficient increases from 0.5 to 2.5, the output cell voltage increases significantly. This behavior can be attributed to enhanced

electrochemical reaction kinetics, as a higher charge transfer coefficient facilitates faster electron transfer at the electrode-electrolyte interface, thereby reducing activation overpotential and improving overall cell performance.

3.7. Impact of Operating Temperature on Water Transport

During PEMFC operation, water is transported within the fuel cell, and its accurate determination is not straightforward. Therefore, the water molar fraction is considered in this study using a one-dimensional (1-D) modeling approach. Figure 15 illustrates the water molar fraction at both the anode and cathode sides. It can be observed that as the operating current density increases, the water molar fraction at the anode side tends to decrease. In contrast, increasing the operating temperature leads to a higher water molar fraction at the anode, as shown in Figure 15a. This behavior can be attributed to enhanced electrochemical reactions and improved electrical conductivity at elevated temperatures. Additionally, water generated at the cathode is partially transported to the anode through the membrane due to the back-diffusion phenomenon, which contributes to the water content at the anode side. However, when the fuel cell operates at a very high temperature of 90 °C, membrane dehydration occurs, resulting in a reduction in the anode water molar fraction. Therefore, effective water management within the fuel cell is crucial for optimizing the output cell voltage and ensuring stable PEMFC performance.

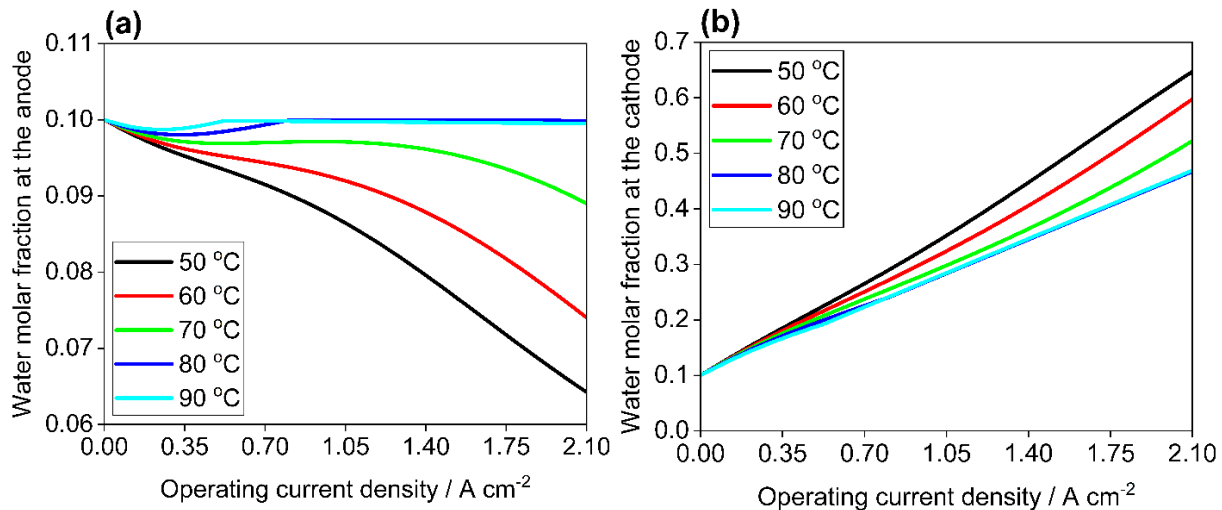


Figure 15. Water transport in the PEMFC under different operating temperatures.

3.8. Molar Fraction of Species in PEMFC

During PEMFC operation, the molar fractions of species vary significantly and depend on the operating conditions. The molar fraction of each species represents its relative content within the fuel cell during operation. In this section, to analyze species molar fractions in the PEMFC, the operating conditions were fixed at an operating temperature of 60 °C and both anode and cathode pressures of 1.2 atm. Figure 16 illustrates the relationship between operating current density and species molar fractions, including hydrogen at the anode, oxygen at the cathode, and water at both the anode and cathode sides. It can be observed that as the operating current density increases from 0 to 2.1 A cm⁻², the hydrogen molar fraction at the anode gradually decreases from 0.9 to 0.8 due to increased fuel utilization under higher load conditions. Similarly, the oxygen molar fraction at the cathode decreases with increasing current density, as more oxygen is consumed to sustain the electrochemical reaction. In contrast, the water molar fraction at the cathode increases significantly, reflecting enhanced water generation as a reaction product. Meanwhile, the water molar fraction at the anode decreases slightly, although the variation is not pronounced due to water transport from the cathode to the anode through back-diffusion. Overall, to optimize PEMFC performance under dynamic load operation, it is essential to consider the molar fractions of gas species and ensure sufficient reactant availability to sustain efficient electrochemical reactions.

3.9. Sensitivity Analysis of the Model

For a PEMFC model, parameter sensitivity can be evaluated by quantifying the variation in the model output caused by changes in a specific parameter. The normalized sensitivity coefficient in this study can be determined using Eq. (54).

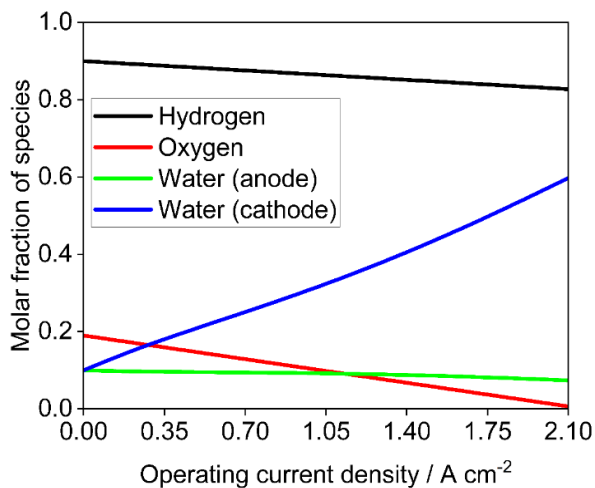
$$S_x = \frac{\Delta Y/Y}{\Delta x/x} \quad (54)$$

where, S_x is the sensitivity coefficient of parameter x ; ΔY denotes the voltage change of the PEMFC; Y represents the PEMFC output voltage; Δx is the change in parameter.

In this model, the sensitivity analysis was evaluated at an operating current density of 1.4 A cm⁻². The sensitivity of key parameters on PEMFC performance under varying operating conditions, including operating temperature, operating pressure (both of pressure, anode pressure and cathode pressure), catalyst layer thickness, exchange current density, and transfer coefficient, is summarized in Table 5. It can be observed that the variations in most investigated parameters resulted in positive sensitivity values, indicating a linear improvement in PEMFC performance with increasing parameter values. The sensitivity coefficients of PEMFC output voltage were positive when increasing the anode pressure, catalyst layer thickness, exchange current density, and transfer coefficient. This can be attributed to the enhanced electrochemical reaction and improved mass transport processes as these key parameters increased, thereby improving overall PEMFC performance.

Table 5. Sensitivity of the operating parameters on PEMFC performance

Parameter	Symbol	Value	Variation / %	Voltage change / %	Sensitivity
Operating temperature / °C	$T_{cell} - 273$	50, 60, 70, 80, 90	+ (20, 16.67, 14.29, 12.5)	+14.57, +5.58, +0.33, -2.08	+0.73, +0.33, +0.02, -0.17
Both of the pressures / atm	$P_A; P_C$	0.9, 1.1, 1.4, 1.6	+ (22.22, 27.27, 14.29)	+3.89, +1.78, -0.15	+0.18, 0.07, -0.01
Anode pressure / atm	P_A	1.0, 1.2, 1.4, 1.6	+ (20, 16.67, 14.29)	+3.15, +2.46, +2.58	+0.16, +0.15, +0.18
Cathode pressure / atm	P_C	1.0, 1.2, 1.4, 1.6	+ (20, 16.67, 14.29)	-0.72, -2.07, -3.66	-0.04, -0.12, -0.256
Catalyst layer thickness / μm	$t^A; t^C$	350, 450, 550, 650, 750, 950	+ (28.57, 22.22, 18.18, 18.38, 26.67)	+10.99, +1.84, +0.66, +0.68, +1.33	+0.38, +0.08, +0.04, +0.04, +0.05
Exchange current density / A cm^{-2}	i_{ref}	0.2, 0.4, 0.6, 0.8, 1.0	+ (100, 50, 33.33, 25.0)	+1.21, +0.70, +0.49, +0.38	+0.012, +0.014, +0.015, +0.015
Transfer coefficient	$\alpha_{Rec,C}; \alpha_{Ox,C}$	0.5, 1.0, 1.5, 2.0, 2.5	+ (100, 50, 33.33, 25.0)	+104.96, +17.07, +7.29, +4.08	+1.05, +0.34, +0.22, +0.16

**Figure 16.** Molar fraction of species under varying load levels

The sensitivity coefficient of operating temperature was -0.17 when the temperature increased from 80 °C to 90 °C . This negative sensitivity is attributed to the degradation of PEMFC performance at temperatures exceeding the optimal operating temperature of 80 °C . At elevated temperatures, membrane dehydration may occur, resulting in reduced proton conductivity and increased ohmic overpotential. Additionally, the sensitivity coefficient of cathode operating pressure was negative because PEMFC performance tends to decrease at high cathode pressure under high current density conditions, leading to increased performance degradation. However, the magnitude of this sensitivity value was relatively small, indicating an insignificant effect.

3.10. Model Application for an Electric Motorcycle

After validating the one-dimensional (1-D) model, it was applied to a hydrogen fuel cell electric motorcycle to analyze its dynamic performance under a driving cycle test. **Figure 17** illustrates the dynamic behavior of the hydrogen fuel cell electric motorcycle, including the traction force and resistance forces during operation. It can be observed that the rolling resistance and slope climbing resistance remain constant throughout the driving cycle, with magnitudes of 29.02 N and 230.85 N , respectively.

In contrast, the aerodynamic (wind) resistance and acceleration forces vary and fluctuate according to the motorcycle's speed and acceleration profiles. The sum of all resistance forces corresponds to the required traction force, which reaches a maximum value of approximately 1033.21 N at 1139 s .

Figure 18 illustrates the dynamic response of the hydrogen fuel cell power source in the electric motorcycle, showing the variation of stack voltage under the World Motorcycle Test Cycle (WMTC). It can be observed that the fuel cell stack voltage varies in accordance with the operating current density. As the operating current density increases, the stack voltage decreases due to increased overpotentials within the fuel cell. In addition, higher current densities lead to greater water generation in the flow field channels, which may accumulate and reduce the effective electrochemically active area while restricting the supply of fresh reactant gases, thereby further

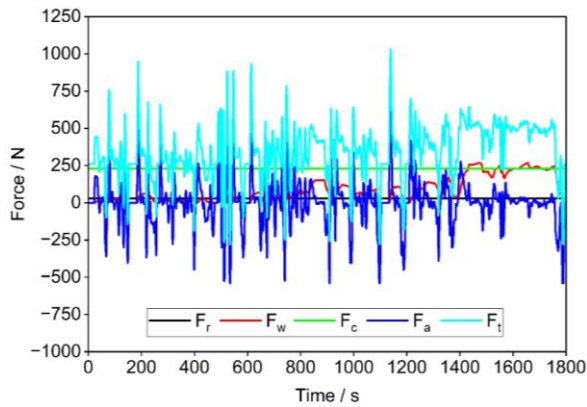


Figure 17. Fuel cell electric motorcycle dynamics under WMTC

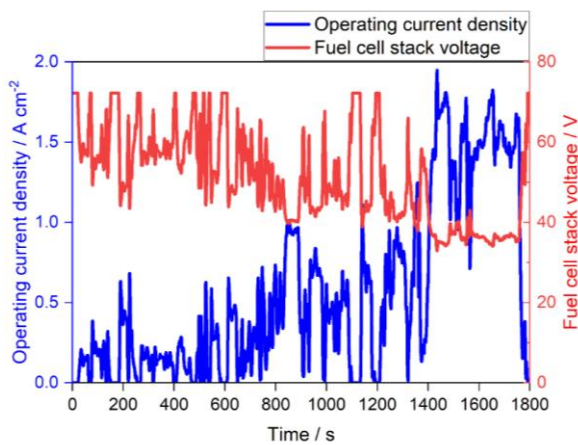


Figure 18. Fuel cell electric motorcycle voltage under operating current density dynamic in WMTC

decreasing the stack voltage. In contrast, under low load conditions, the fuel cell stack voltage remains at a higher level due to reduced overpotentials. Moreover, moderate water generation is sufficient to maintain membrane humidification, which enhances proton conductivity and results in improved fuel cell stack performance.

Figure 19 presents the overpotential voltages of the hydrogen fuel cell electric motorcycle under the World Motorcycle Test Cycle (WMTC). It can be observed that the ohmic voltage loss is more pronounced than both the activation and concentration voltage losses. In addition, the ohmic loss exhibits significant variation throughout the WMTC. All three overpotential components fluctuate in response to the dynamic driving conditions. At high load levels, particularly between 1400 s and 1800 s, the concentration overpotential increases sharply due to mass transport limitations under elevated current demand.

Figure 20 illustrates the molar fractions of gas species and water within the fuel cell stack of the electric motorcycle, highlighting species transport during dynamic operation. The molar fractions of hydrogen and oxygen vary in accordance with the operating current density. At higher load levels, the molar fractions of hydrogen and oxygen decrease due to increased reactant consumption to sustain the electrochemical reactions within the stack. In contrast, the molar fractions of water at both the anode and cathode sides increase as the operating current density rises. Notably, the water molar fraction at the cathode side is more pronounced than that at the anode. This behavior results from water generation as a product of the electrochemical reaction at the cathode, as well as water transport from the anode to the cathode via the electro-osmotic drag phenomenon. The average water molar fraction at the cathode side is approximately 0.268.

During the operation of the hydrogen fuel cell electric motorcycle, variations in load demand

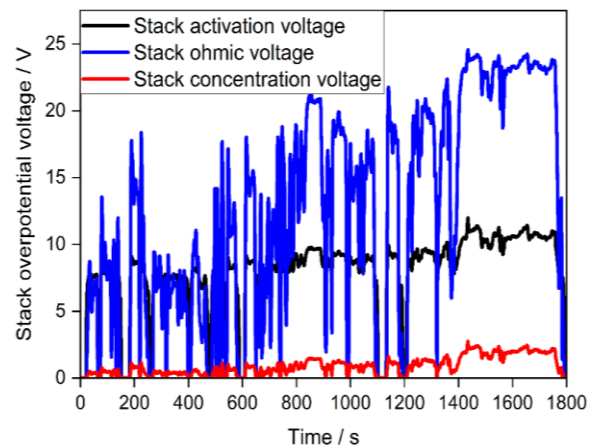


Figure 19. Fuel cell electric motorcycle overpotential voltage under WMTC

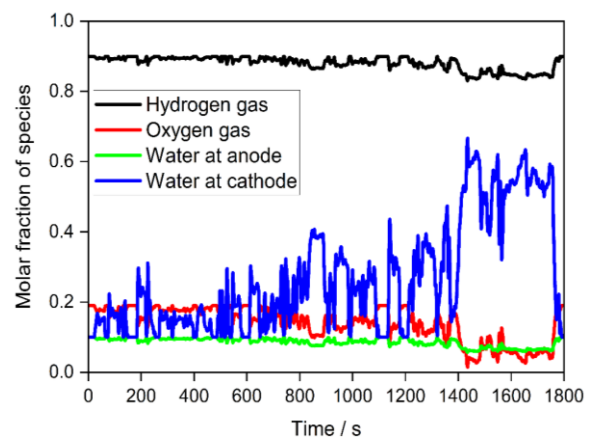


Figure 20. Molar fraction of species under WMTC

lead to corresponding changes in hydrogen consumption due to the electrochemical reactions within the fuel cell. Therefore, hydrogen utilization is considered in this study. **Figure 21** illustrates the hydrogen consumption as a function of operating current density under the WMTC driving cycle. It can be observed that hydrogen consumption increases with rising operating current density, as higher load levels require a greater amount of hydrogen to sustain the electrochemical reaction. The average hydrogen consumption is approximately 0.174 g s^{-1} .

Additionally, water generation resulting from the electrochemical reaction is considered in this study, as it directly affects fuel cell stack performance. **Figure 22** illustrates the relationship between operating current density and water generation rate. It can be observed that water

generation increases significantly with rising load level due to the intensified electrochemical reaction within the fuel cell stack. At high load levels, particularly between the 1400th and 1800th seconds, the average water generation rate reaches approximately 1.946 g s^{-1} .

Ultimately, the stack energy efficiency was evaluated under the WMTC driving cycle. **Figure 23** presents the relationship between operating current density and stack energy efficiency during the driving cycle test. The results indicate that stack energy efficiency decreases as the operating current density increases. This decline is primarily attributed to excessive water generation and accumulation in the flow field channels, which reduces the effective active area of the cell and restricts the transport of freshly supplied reactant gases, thereby deteriorating the overall stack performance.

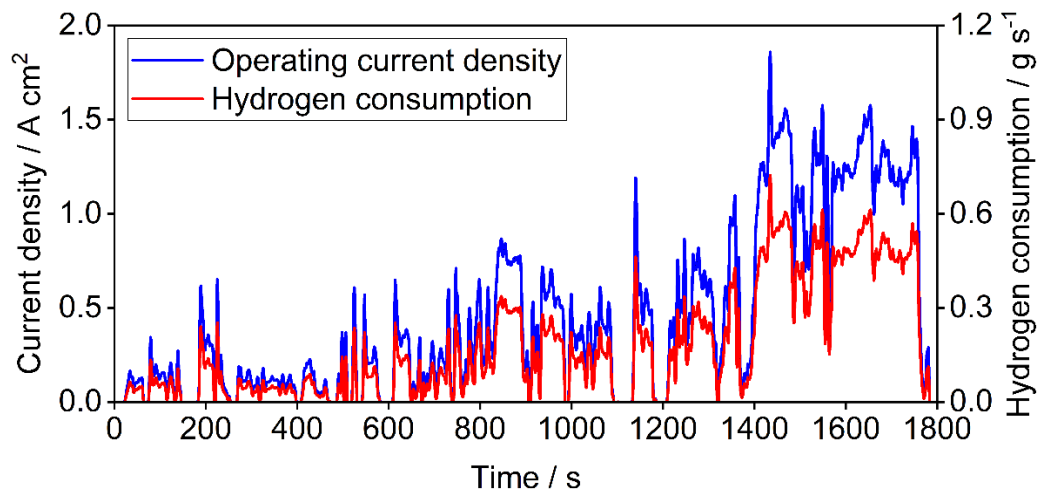


Figure 21. Hydrogen consumption of fuel cell electric motorcycle under WMTC

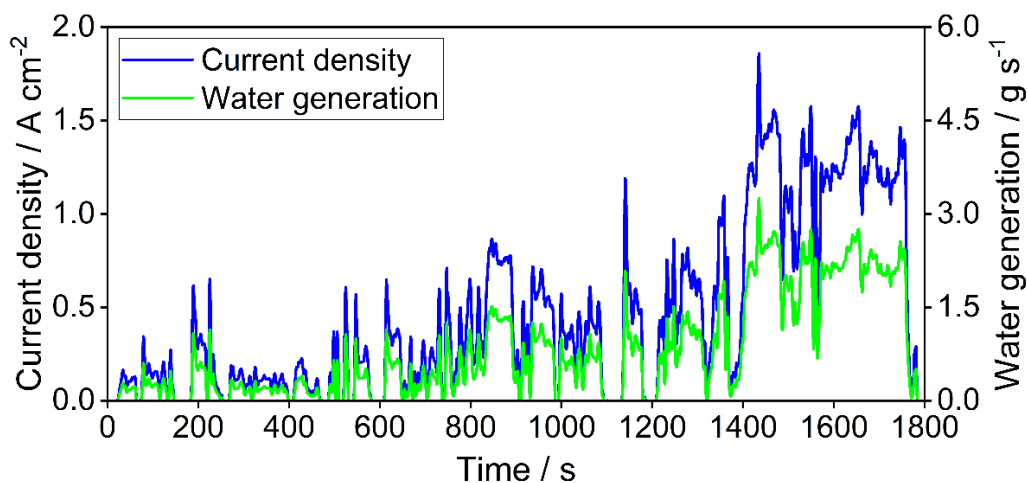


Figure 22. Water generation of fuel cell electric motorcycle under WMTC

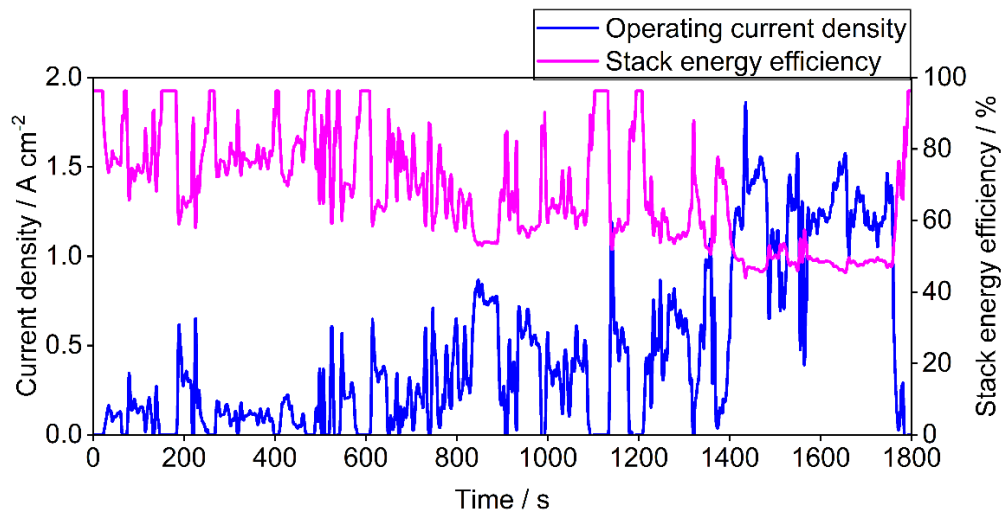


Figure 23. Fuel cell stack energy efficiency under WMTC

4. Conclusion

In this study, the effects of operating conditions on PEMFC performance were investigated using MATLAB software based on a one-dimensional (1-D) modeling approach. Several conclusions can be drawn as follows:

- a. An increase in operating temperature improves cell performance due to enhanced electrical conductivity and accelerated electrochemical reactions. However, when the fuel cell operates at excessively high temperatures, performance deteriorates because membrane dehydration occurs, leading to reduced proton conductivity. In this study, the best-performing operating temperature within the examined range was identified as 80 °C.
- b. Operating pressure has a significant influence on PEMFC performance. Increasing the operating pressure enhances cell performance by improving reactant availability. Nevertheless, under high operating pressure combined with high load levels, excessive water generation and accelerated catalyst layer corrosion occur, resulting in performance degradation.
- c. When the fuel cell operates at high load levels, PEMFC performance declines due to increased voltage losses, including activation, ohmic, and concentration overpotentials.
- d. The effects of reference exchange current density, charge transfer coefficient, and membrane thickness were examined. Higher values of reference exchange current density and charge transfer coefficient enhance

electrochemical reaction rates, while increased membrane thickness improves water retention and membrane hydration, collectively contributing to improved cell performance.

- e. The molar fractions of gas species were analyzed under various operating conditions. In particular, water molar fraction distributions at the anode and cathode sides were investigated to clarify water transport behavior and its influence on PEMFC performance.
- f. The validated 1-D PEMFC model was applied to evaluate the dynamic performance of a hydrogen fuel cell electric motorcycle under the World Motorcycle Test Cycle (WMTC), including traction demand, hydrogen consumption, water generation, and fuel cell stack energy efficiency.

Overall, this study provides meaningful insights into PEMFC performance under different operating conditions. The developed model effectively predicts steady-state PEMFC performance and internal water transport phenomena. Furthermore, the model was successfully extended to analyze the dynamic performance characteristics of a hydrogen fuel cell electric motorcycle under realistic driving cycle conditions. Although the 1-D model has been developed in this study, it still has limitations. The polarization curves of the PEMFC were deployed in the published papers to validate the model results trend. In future works, the PEMFC performance of the electric motorcycle under the dynamic driving cycle test will be carried out to improve the mathematical model.

Author's Declaration

Authors' contributions and responsibilities

The authors made substantial contributions to the conception and design of the study. The authors were responsible for data analysis, interpretation, and discussion of the results. The authors read and approved the final manuscript.

Funding

The authors did not receive support from any organization for the submitted work.

Availability of data and materials

All data are available from the authors.

Competing interests

The authors declare no competing interest.

Generative AI statement

The author(s) declare that no generative AI or AI-assisted technologies were used in the preparation of this manuscript.

Additional information

No additional information from the authors.

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