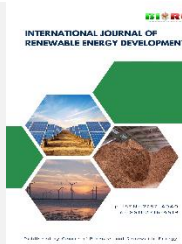




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Research Article

Study on water transport and optimization of water management strategy to improve performance of a proton exchange membrane fuel cell

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Abstract. Proton exchange membrane fuel cells (PEMFCs) are considered a promising energy source for future applications due to their outstanding characteristics. During PEMFC operation, in addition to electricity and heat generation, water is produced through electrochemical reactions within the fuel cell, which significantly influences cell performance. Therefore, water generation and transport must be carefully considered. In this study, a mathematical model of PEMFC performance coupled with a water transport model is developed to evaluate fuel cell performance and water transport dynamics under driving cycle conditions. The results indicate that PEMFC performance is strongly affected by water generation, with higher operating current densities and longer operating durations leading to increased water production. At the highest operating current density of 0.78 A cm^{-2} under driving cycle condition, the anode and cathode water generation rates reach 7.491×10^{-8} and $9.779 \times 10^{-11} \text{ m}^3 \text{ s}^{-1}$, respectively. Furthermore, an optimization of the water management strategy for PEMFCs is proposed based on the ratio of cathode water volume to anode water volume at maximum cell performance. The optimal ratio is found to be 1.63% at an operating current density of 1.2 A cm^{-2} in this study. When the operating current density exceeds 1.2 A cm^{-2} , the cell performance declines significantly due to excessive water accumulation, which can induce flooding within the PEMFC. This flooding reduces the effective electrochemically active area and restricts the supply of fresh reactant gases to the flow field channels, ultimately leading to performance degradation. Overall, this study provides valuable insights into achieving optimal PEMFC performance by explicitly accounting for water generation and management.

Keywords: proton exchange membrane fuel cell; water transport; water generation; water management; fuel cell performance; driving cycle; optimization of water; water management strategy



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1. Introduction

The proton exchange membrane fuel cell (PEMFC) is considered to be a promising energy source in the future owing to its highlighted properties, including the low temperature operation, zero-emission, high energy efficiency, high power density, and quick start-up (Barbir 2012). Recently, PEMFC has been applied in many applications, such as a stationary power source (Loskutov *et al.* 2024; Wang, Kuo, and Chen 2013), portable power source (Devrim, Devrim, and Eroglu 2015; Sohn *et al.* 2005), unmanned underwater vehicles (UUVs) (Kwon *et al.* 2024; Liu, Zhao, and Tu 2024; Tu *et al.* 2024), unmanned aerospace vehicles (UAVs) (Ferreira *et al.* 2024; Tu *et al.* 2025; Mariscal *et al.* 2024), tramway (Mariscal *et al.* 2024; Han *et al.* 2017; Zhang *et al.* 2020), and automobile (Wang and Wang 2024; Kocha 2012).

During the PEMFC operation, it was affected by many operating conditions, such as temperature, pressure, designed components, and system management. Indeed, Askaripour, Yan, and Amirinejad *et al.* (Askaripour 2019; Yan, Toghiani, and Causey 2006; Amirinejad, Rowshanzamir, and Eikani 2006) studied the effect of operating conditions on the PEMFC

performance, including the pressure, temperature, humidity, and stoichiometry ratio. Coppo *et al.* (Coppo, Siegel, and Von Spakovsky 2006) developed the model and experimental validation to evaluate the effect of temperature on the PEMFC performance under varying operating temperatures. They considered the removal of liquid water and liquid water transport in the fuel cell and concluded that the model is in good agreement with the experiment, and their model can be used to predict the temperature-dependent parameters. Chugh *et al.* (Chugh *et al.* 2020) developed the mathematical model using the MATLAB software. Their model is then to be validated by a series of experiments under different operating temperatures. They revealed that their model has achieved low error, with ranging 7 to 15%. Zhao *et al.* (Zhao *et al.* 2015) studied and analyzed the sensitivity of the effect of local temperature distribution on the PEMFC performance of 1.2 kW. They indicated that the operating temperature not only significantly affected the performance but also impacted the water vapor in the fuel cell. Park *et al.* (Park and Li 2006) developed a non-isothermal temperature mathematical model to analyze the effect of temperature on the fuel cell performance. Their results show that the operating temperature has a dominant impact on

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the fuel cell voltage. Kim *et al.* (Kim and Hong 2008) investigated the effect of operating temperature and humidity on the PEMFC stack with 10 cells and an activation area of 10 cm². They concluded that the PEMFC performance was impacted significantly when the temperature and humidity increased. Similarly, Ozen *et al.* (Ozen, Timurkutluk, and Altinisik 2016) studied the effect of temperature and humidity on the performance of the PEMFC with a cell activation area of 25 cm². They indicated that when the operating temperature and humidity elevated, the cell performance improved. Shan *et al.* (Shan and Choe 2006) developed a mathematical model to analyze the effect of operating temperature on fuel cell performance. Their results show that the temperature is distributed asymmetrically in the fuel cell. They suggested the new design to enhance the performance of the fuel cell. Tiss *et al.* (Tiss, Chouikh, and Guizani 2013) developed a dynamic model to evaluate the impact of operating temperature on the PEMFC performance by using the MATHCAD software. Their model was compared to the iso thermal and indicated that the model was appropriate to control real-time for the fuel cell system. Hu *et al.* (Hu *et al.* 2021) investigated the optimal operating temperature of the PEMFC in automotive applications. Their results show that the PEMFC energy efficiency improved to 18.2% and 28.7%, corresponding to the New European Driving Cycle (NEDC) and China heavy-duty commercial vehicle test cycle for heavy trucks (CHTC-HT) driving cycles. The investigation of the effect of operating temperature ranging from 23 to 120 °C is carried out by Song *et al.* (Song *et al.* 2007). They indicated that when the temperature increased, the performance improved. However, when the operating temperature increased over 80 °C, the performance declined owing to dehydration. Therefore, they revealed that the optimal operating temperature was achieved at 80 °C. Askaripour *et al.* (Askaripour 2019) developed a two-phase flow model to discuss the effect of operating conditions on the output voltage of PEMFC. Their results show that the cell performance was improved when the operating temperature, pressure, stoichiometry ratio, and humidity increased appropriately. Park *et al.* (Park and Choe 2008) modeled a two-phase flow dynamic model and validated by series a experiments to analyze the effect of operating temperature on the PEMFC performance with 20-cell. Their results show that the temperature gradient was contributed significantly at the last four cells, while the oxygen concentration, water vapor, and water content in the membrane for the rest of cell were uniform. Wang *et al.* (Wang, Sun, and Yang 2025) optimized the temperature distribution in cooling plate of the PEMFC by using the computational study method. They concluded that the when the coolant rate increased, the temperature distribution was more consistency.

Zhou *et al.* (Zhou *et al.* 2006) studied the effect of pressure on the PEMFC performance. Their results show that the pressure drop in the flow field channels can caused increasing the pumping power cost. Quin *et al.* (Qin *et al.* 2017) studied the effect of operating pressure on the power of PEMFC with 20 kW, which is applied for the automobile. They found that the optimal pressure was achieved at 1.2 atm. Taymaz *et al.* (Taymaz and Benli 2010) developed a model to analyze the effect of operating pressure on the output voltage of PEMFC by using computational fluid dynamics (CFD). They revealed that when the operating pressure increased, it could cause GDL destruction. Therefore, the optimal operating pressure plays a crucial role. Ko *et al.* (Ko *et al.* 2018) investigated the effect of operating pressure on the PEMFC performance, considering the water distribution in the fuel cell. They indicated that when the operating pressure increased, leading to penetration of water

transport and a decline in the concentration over potential of the fuel cell. Wahdame *et al.* (Wahdame, Candusso, and Kauffmann 2006) studied the gas pressure in a fuel cell of 500 W. They concluded that the fuel cell power over 1 kW was applied to the compressor is appropriate. Yu *et al.* (Yu *et al.* 2021) studied the pressure drop distribution in the fuel cell. They indicated that the gas distribution was uniform in the empty chamber. Shim *et al.* (Shim, Tsushima, and Hirai 2009) modeled and experimented to evaluate the effect of oxygen pressure on the PEMFC performance and degradation of the fuel cell membrane at the cathode side. They revealed that when the pressure of oxygen elevated, the degradation rate increased owing to corrosion of the catalyst layer. Gou *et al.* (Gou, Pei, and Wang 2006) developed the dynamic model to discuss the effect of pressure during the anode purging process on the PEMFC performance. Their results show that the pressure swing, pressure drop, and distributed pressure increased when the operating pressure increased. Hsieh *et al.* (Hsieh, Her, and Huang 2011) studied the effect of pressure drop in various flow field channels on the water accumulation. They concluded that the type of interdigitated flow field channel was achieved the highest pressure drop.

The water accumulation in the fuel cell significantly impacted the fuel cell performance during the PEMFC operation. Zhan *et al.* (Zhan *et al.* 2012) carried out an experiment to discuss the water transport visualization in a fuel cell. Their results show that the gas flow rate has a significant relationship with the water accumulation. They revealed that the gas velocity exceeded 7 m s⁻¹, and the liquid water could be removed. Shimpalee *et al.* (Shimpalee *et al.* 2004) developed a model to predict the water transport in the fuel cell. They indicated that when the fuel cell operated without humidification, the pressure drop could be declined 30%. Zhang *et al.* (Zhang, Pan, and Quan 2008) proposed the model predictive control to manage the water accumulation in the fuel cell by using MATLAB/Simulink and a Recurrent Neural Network (RNN). They indicated that the proposed RNN method is better than the Proportional Integral Derivative (PID) owing to a short response time that can help avoid fluctuation of water. Siegel *et al.* (Siegel *et al.* 2004) developed a mathematical model to investigate a two-phase flow water transport model in the PEMFC. Their model was then validated by experiments and concluded that the the model was achieved high accuracy.

In recent years, Zeng *et al.* (Zeng *et al.* 2025) studied the water management of the PEMFC by employing the metal foam flow field channel combined with an artificial intelligence (AI) image recognition model. The AI image recognition monitored the flooding phenomenon in the fuel cell and triggered the purge valve to expel the water to the atmosphere. Their results show that the PEMFC performance improved. Wang *et al.* (Wang *et al.* 2024) proposed a novel method that combined deep learning technology and segment cell to diagnostic fault of PEMFC water management. They indicated that the model can detect the flooding and dry fault of the PEMFC with an accuracy of 98.5%. Shao *et al.* (Shao *et al.* 2023) suggested the water management strategy of the PEMFC based on the current mapping under the high temperature and low humidity conditions for heavy-duty vehicles. Their results show that the cell voltage recovered from 0.68 V to 0.74 V. To prevent the local water accumulation, the pressure swing technique that operates pressure fluctuation using the active-deactivated a inlet solenoid valve was proposed by Pei *et al.* (Pei *et al.* 2024). They indicated that the water removal rate was achieved 99.25%. Liu *et al.* (Liu, Tu, and Chan 2023) proposed the gas recirculation using the ejector device in PEMFC. Their results show that the performance increased

4.75%. Zhou *et al.* (Zhou *et al.* 2023) developed an easy-to-implement method by interrupting dry and wet gas during the fuel cell operation. They revealed that the performance of the PEMFC was enhanced by alleviating the water accumulation in the flow field channel. Khanafari *et al.* (Khanafari *et al.* 2024) presented a method to consider the water management in PEMFC by using the adaptive neurofuzzy approximation and fuzzy control. They indicated that the reduction of the flooding and dry out of the membrane declined 48%. Pu *et al.* (Pu *et al.* 2025) proposed a data-driven fault diagnosis method for water management of PEMFC, deploying the Markov Transition Field (MTF) and deep learning. Their results show that the model achieved high accuracy of 99.33%.

Based on previous studies, PEMFC performance is influenced by various operating conditions, especially the water generation. Therefore, enhancing PEMFC performance and water management strategy during operation is necessary and plays a crucial role in practical applications. Although almost all studies have studied the water management of the PEMFC, but still limitations and challenges, because the water transport within the PEMFC is complex. Therefore, the consideration of the water transport model, including the anode water transport, cathode water transport, and water generation, is necessary. In this study, a mathematical model incorporating both performance and water transport is developed to capture the dynamic behavior of PEMFCs under driving cycle conditions. The model is then validated to verify its agreement with reported results. Finally, an optimization of the water management strategy is proposed to achieve optimal PEMFC performance by accounting for dynamic water transport within the fuel cell. This study provides valuable insights into optimizing fuel cell performance by maintaining adequate membrane hydration while preventing flooding phenomena within the fuel cell.

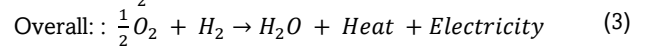
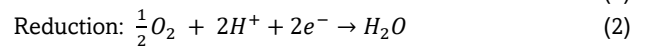
2. Method

2.1 Proton exchange membrane fuel cell model

Fig. 1(a) illustrates an exploded view of the fuel cell components considered in this study, arranged from the outermost to the innermost layers. Bolts are used to fasten and compress the fuel cell assembly, while end plates serve as structural covers. The bipolar plates are responsible for distributing the reactant gases through the flow field channels. Plastic gaskets are incorporated to prevent gas leakage. Gas diffusion layers (GDLs) are placed to facilitate gas transport and protect the catalyst layer from

corrosion during fuel cell operation. At the core of the assembly is the membrane electrode assembly (MEA), which consists of a proton exchange membrane coated with catalyst layers on both sides.

A proton exchange membrane fuel cell (PEMFC) directly converts electrochemical energy into electrical energy through electrochemical reactions. During operation, heat and water are simultaneously generated as by-products. Hydrogen is supplied to the anode, while oxygen or air is supplied to the cathode. The outputs of the PEMFC included electricity, heat, and water, as illustrated in Fig. 1(b), in accordance with the principle of energy balance. Eqs. (1) and (2) describe the oxidation and reduction reactions occurring at the anode and cathode, respectively, while Eq. (3) represents the overall electrochemical reaction of the PEMFC.



The output voltage of the PEMFC (V_{cell}), in V, was determined by Eq. (4). It consisted of the open-circuit voltage (OCV), also called the reversible voltage, minus the summation of the overpotential in the PEMFC during its operation:

$$V_{cell} = E_0 - (V_{act} + V_{ohm} + V_{conc}) \quad (4)$$

Where: E_0 , V_{act} , V_{ohm} , and V_{conc} represent the OCV, activation voltage loss, ohmic voltage loss, and concentration voltage loss, respectively. All parameters are in units of V.

At the standard condition with operating pressure of 1 atm, and operating temperature of 25 °C, the highest PEMFC voltage was achieved at standard condition, which is called reversible voltage, and was determined by Eq. (5) (Zhang, Wu, and Zhang 2013), as follows:

$$E_0 = \frac{-\Delta G}{nF} = 1.229 \text{ V} \quad (5)$$

Where: ΔG represents the Gibbs free energy owing to the reaction of electrochemical in PEMFC ($\Delta G = -237340$), in (J mol⁻¹); n is the exchanged electron number ($n = 2$); and F denotes Faraday's constant ($F = 96485 \text{ J mol}^{-1}$).

In practice, the PEMFC operated in different conditions of operating pressure and temperature. Therefore, the OCV is affected significantly, and it can be determined following the

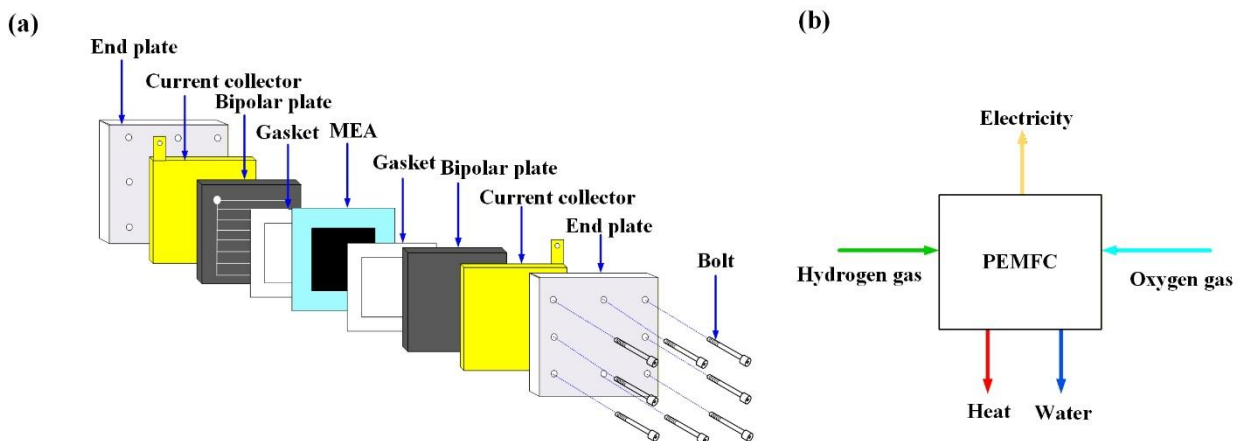


Fig. 1 Exploded view of PEMFC components (a); Illustration of the energy balance principle in PEMFC

Nernst equation (Pukrushpan, Stefanopoulou, and Peng 2004; Amphlett *et al.* 1995b):

$$E_0 = 1.229 - 0.85 \times 10^{-3}(T_{fc} - 298.15) + 4.3085 \times 10^{-5} T_{fc} \left[\ln(P_{H_2}) + \frac{1}{2} \ln(P_{O_2}) \right] \quad (6)$$

Where: T_{fc} is the operating temperature of the PEMFC, in K; P_{H_2} denotes the partial pressure of the hydrogen at the anode side, in atm; and P_{O_2} represents the partial pressure of oxygen at the cathode side, in atm.

The activation voltage loss occurred during the PEMFC operation at the low load levels. It depends significantly on the partial pressure of oxygen (Amphlett *et al.* 1995a) and temperature (Kordesch and Simader 1996). It can be calculated by Eq. (7):

$$V_{act} = V_0 + V_a (1 - \exp(-c_1 \times i_{fc})) \quad (7)$$

Where: V_0 denotes the voltage drop at zero current density, in V; and V_a represents the contributed activation voltage loss, in V, c_1 is the activation loss constant value, and i_{fc} refers to the operating current density of the fuel cell, in A cm⁻². These parameters were defined as follows:

$$V_0 = 0.279 - 8.5 \times 10^{-4}(T_{fc} - 298.15) + 4.308 \times 10^{-5} T_{fc} \times \left[\ln\left(\frac{P_{ca} - P_{sat}}{1.01325}\right) + \frac{1}{2} \ln\left(0.01173 \frac{P_{ca} - P_{sat}}{1.01325}\right) \right] \quad (8)$$

$$V_a = (-1.618 \times 10^{-5} T_{fc} + 1.618 \times 10^{-2}) \left(\frac{P_{O_2}}{0.1173 + P_{sat}} \right)^2 \quad (9)$$

$$i_{fc} = \frac{I_{fc}}{A_{fc}} \quad (10)$$

Where: P_{ca} is the operating cathode pressure, in atm; P_{sat} denotes the saturated water vapor pressure, in atm; I_{fc} refers to the operating current load level, in A; and A_{fc} is the cell activation area, in cm².

The saturated water vapor in the PEMFC can be determined by Eq. (11) (Springer, Zawodzinski, and Gottesfeld 1991a), as follows:

$$P_{sat} = 10^{-2.1794 + 0.02953(T_{fc} - 273.2) - 9.1837 \times 10^{-5}(T_{fc} - 273.2)^2 + 1.4454 \times 10^{-7}(T_{fc} - 273.2)^3} \quad (11)$$

The ohmic voltage loss represents the voltage loss owing to the resistance of the membrane. It depends on the cell temperature (Amphlett *et al.* 1994; Laurencelle *et al.* 2001) and membrane humidity (Laurencelle *et al.* 2001). Eq. (12) expressed the ohmic voltage loss for the PEMFC:

$$V_{ohm} = i_{fc} \times R_{ohm} = \frac{\delta_m}{\sigma_m} \times i_{fc} \quad (12)$$

Where: R_{ohm} is the internal electrical resistance, in Ω cm²; δ_m denotes the thickness of the membrane, in cm; and σ_m refers to the membrane conductivity, in $(\Omega \text{ cm})^{-1}$.

The membrane conductivity of the PEMFC depends significantly on the fuel cell temperature and water content in the membrane. It can be determined by Eq. (13) (Springer, Zawodzinski, and Gottesfeld 1991b):

$$\sigma_m = b_1 \left(b_2 \left(\frac{1}{303} - \frac{1}{T_{fc}} \right) \right) \quad (13)$$

Where: b_1 , and b_2 represent the membrane conductivity constant value that is determined by the empirical method. Additionally, b_2 depends on the water content in the membrane, and can be calculated by Eq. (14), as follows:

$$b_1 = 0.005139 \lambda_m - 0.00326 \quad (14)$$

The concentration voltage loss occurred during the fuel cell operation at a high load level and can be determined by Eq. (15):

$$V_{conc} = i_{fc} c_2 \left(\frac{i_{fc}}{i_{fcmax}} \right)^{c_3} \quad (15)$$

Where: c_2 and c_3 are the concentration loss constant values; i_{fcmax} represents the maximum operating current density of the PEMFC, in A cm⁻².

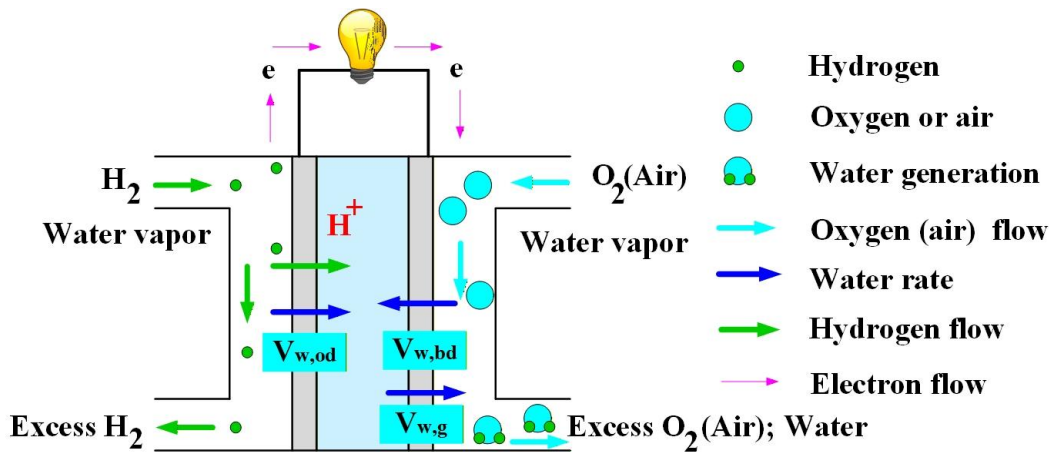


Fig. 2 Illustration of the water transport model in PEMFC

The concentration loss constant value depends on the operating conditions, and it was determined as follows (Pukrushpan, Stefanopoulou, and Peng 2004):

$$c_2 = \begin{cases} (7.15 \times 10^{-4} T_{fc} - 0.622) \left(\frac{P_{O_2}}{0.1173 + P_{sat}} \right) \\ (-1.45 \times 10^{-3} T_{fc} + 1.68) & \text{for } \frac{P_{O_2}}{0.1173 + P_{sat}} \\ (8.66 \times 10^{-5} T_{fc} - 0.068) \left(\frac{P_{O_2}}{0.1173 + P_{sat}} \right) \\ (-1.6 \times 10^{-4} T_{fc} + 0.54) & \text{for } \frac{P_{O_2}}{0.1173 + P_{sat}} \end{cases} \quad (16)$$

2.2 Water transport model

Fig. 2 illustrates the water transport in the PEMFC, including the anode water generation, cathode water generation, and transport within the cell. The total volume of water accumulation in the anode and cathode sides, based on the water balance principle, includes the water generation from the electrochemical reaction of the PEMFC ($V_{w,g}$), the water volume due to the osmotic-drag phenomenon from the anode side to the cathode side ($V_{w,od}$), and the water volume caused by the back-diffusion phenomenon from the cathode to the anode ($V_{w,bd}$). Eq. (17) and (18) were proposed to determine the contribution of water at the anode side and cathode side, respectively:

$$V_a = V_{w,bd} - V_{w,od} \quad (17)$$

$$V_c = V_{w,g} + V_{w,od} - V_{w,bd} \quad (18)$$

During the PEMFC operation, the back diffusion of water volume from the cathode to the anode side can be determined using Eq. (19):

$$V_{w,bd} = -\frac{\rho_m}{M_m} D_m \frac{d\lambda_m}{dz \rho_{H_2O}} M_{H_2O} t_{pi} 10^{-3} \quad (19)$$

Where ρ_m is the density of dry membrane, in kg cm^{-3} ; M_m is the equivalent weight of the Nafion membrane, in kg mol^{-1} . These values were provided by the manufacturer's specifications. M_{H_2O} denotes the molecular weight of water, in g mol^{-1} ; ρ_{H_2O} represents the water density, in kg m^{-3} ; and t_{pi} refers to the fuel cell operating time, in s. The symbol z is the direction through the thickness of the membrane, in cm; and D_m , in $\text{cm}^2 \text{s}^{-1}$, is the diffusion coefficient, which depends significantly on the water content in the membrane, and is determined as follows (Barzegari *et al.* 2016):

$$D_m = D_0 \exp \left(2416 \left(\frac{1}{303} - \frac{1}{T_m} \right) \right) \quad (20)$$

$$D_0 = \begin{cases} 10^{-10}, & \lambda_m < 2 \\ 10^{-10} (1 + 2(\lambda_m - 2)), & 2 \leq \lambda_m \leq 3 \\ 10^{-10} (3 - 1.67(\lambda_m - 3)), & 3 < \lambda_m \leq 4.5 \\ 1.25 \times 10^{-10}, & \lambda_m > 4.5 \end{cases} \quad (21)$$

Where: λ_m represents the water content in the membrane.

The volume of water generated from the electrochemical reaction ($V_{w,g}$), in m^3 , can be calculated by Eq. (22):

$$V_{w,g} = \frac{I_{cell}}{2F\rho_{H_2O}} M_{H_2O} t_{pi} 10^{-3} \quad (22)$$

Where I_{cell} denotes the operating current of the fuel cell, in A. The water volume due to the electro-osmotic drag phenomenon ($V_{w,od}$), in m^3 , was defined as Eq. (23):

$$V_{w,od} = 2n_d \frac{I_{cell}}{2F\rho_{H_2O}} M_{H_2O} t_{pi} 10^{-3} \quad (23)$$

Where n_d represents the electro-osmotic coefficient, and it can be determined by Eq. (24) and depends on the water content λ_m . The water content in the membrane can be defined by Eq. (25) (Zhu *et al.* 2019). The water activity was defined as Eq. (26):

$$n_d = n_d^* \frac{\lambda_m}{22} \quad \text{with } 0 < \lambda_m < 22, \quad n_d^* = 2.5 \quad (24)$$

$$\begin{cases} \lambda_m = 0.043 + 17.81\phi_{w(m)} - 39.85\phi_{w(m)}^2 + 36\phi_{w(m)} \\ \lambda_m = 14 + 1.4(\phi_{w(m)} - 1) \end{cases} \quad (25)$$

$$\phi_{w(m)} = \frac{p^*}{P_{sat}} \quad (26)$$

Where λ_m , $\phi_{w(m)}$, p^* , and P_{sat} denote the water content in the membrane, the water activity in the membrane, the partial pressure of water vapor, and the saturated water vapor pressure, respectively. The saturated water vapor pressure depends on the cell temperature and can be determined from thermodynamic tables or calculated by Eq. (11)

Generally, the water activity can be determined by calculating the average value between the water activation at the anode and cathode sides, and is achieved at 0.5 (Zhu *et al.* 2019). It can be determined by Eq. (27), as follows:

$$\phi_{w(m)} = \frac{\phi_{w(a)} + \phi_{w(c)}}{2} \quad (27)$$

Where: $\phi_{w(a)}$ and $\phi_{w(c)}$ represent the water activity at the anode and cathode sides, respectively.

Combining Eq. (19) and Eq. (23), the water volume owing to the electro-osmotic drag phenomenon from the anode side to the cathode side and the volume of water due to the back-diffusion phenomenon from the cathode to the anode can be determined as follows:

$$\begin{aligned} V_{w,od} + V_{w,bd} &= 2n_d \frac{I_{cell}}{2F\rho_{H_2O}} M_{H_2O} t_{pi} 10^{-3} \\ &\quad - \frac{\rho_m}{M_m} D_m \frac{d\lambda_m}{dz \rho_{H_2O}} M_{H_2O} t_{pi} 10^{-3} \\ &= \frac{\tau I_{cell}}{2F\rho_{H_2O}} M_{H_2O} t_{pi} 10^{-3} \end{aligned} \quad (28)$$

Where τ represents the ratio of the net water flux in the membrane to the water flux produced at the cathode side. This parameter serves as a key factor influencing the water content at the cathode side in this study. Upon rearranging Eq. (28), the resulting equation was obtained:

$$\frac{d\lambda_m}{dz} = \left(2n_d^* \frac{\lambda_m}{22} - \tau \right) \frac{I_{cell} M_m \rho_{H_2O}}{2F\rho_m D_m M_{H_2O} t_{pi} 10^{-3}} \quad (29)$$

From Eq. (30), the simple form can be expressed as follows:

$$\frac{d\lambda_m}{dz} = \left(2n_d^* \frac{\lambda_m}{22} - \tau\right) K \quad (30)$$

Where: K denotes the term value of the outside bracket, which was described by Eq. (31)

$$K = \frac{I_{cell} M_m \rho_{H_2O}}{2F \rho_m D_m M_{H_2O} t_{pi} 10^{-3}} \quad (31)$$

Therefore, Eq. (30) can be arranged into the form:

$$\begin{aligned} \frac{d\lambda_m}{dz} &= \left(2n_d^* \frac{\lambda_m}{22} - \tau\right) K = K 2n_d^* \frac{\lambda_m}{22} - K\tau \\ &= A\lambda_m - B \end{aligned} \quad (32)$$

Where: $A = \frac{K 2n_d^*}{22}$ and $B = K\tau$ denote the constant value.

Eq. (32) represents first-order linear differential equations. By solving it, the water content in the membrane can be expressed as follows:

$$\lambda_m(z) = \frac{11\tau}{n_d^*} + C \exp\left[\frac{2n_d^* I_{cell} M_m \rho_{H_2O}}{22F 2\rho_m D_m M_{H_2O} t_{pi} 10^{-3}} z\right] \quad (33)$$

Where C is the constant, which was determined based on the boundary conditions and operating conditions. Indeed, it was calculated at $z = 0$ and $z = \delta_m$. Where: δ_m is the thickness of the membrane (cm).

Therefore, the water volume at the anode and cathode sides can be expressed, corresponding to Eqs. (34) and (35):

$$\begin{aligned} V_a = V_{w,bd} - V_{w,od} &= 2n_d \frac{I_{cell}}{2F \rho_{H_2O}} M_{H_2O} t_{pi} 10^{-3} \\ &+ \left(2n_d^* \frac{\lambda_m}{22} - \tau\right) \frac{I_{cell}}{2F} \end{aligned} \quad (34)$$

$$\begin{aligned} V_c = V_{w,g} + V_{w,od} - V_{w,bd} \\ = (1 + \tau) \frac{I_{cell}}{2F \rho_{H_2O}} 10^{-3} M_{H_2O} t_{pi} \end{aligned} \quad (35)$$

In this study, a water management strategy is proposed to optimize the power density of the fuel cell based on the ratio of the cathode water volume to the anode water volume. In other words, an appropriate fraction of the water generated at the cathode is utilized to sufficiently humidify the membrane, thereby preventing membrane dehydration and enabling the fuel cell to achieve its maximum power density. This relationship can be expressed by Eq. (36).

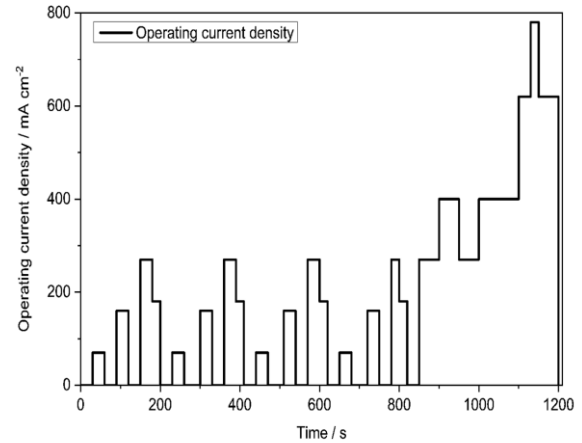


Fig. 3 Operating current density profile in driving cycle test

$$\begin{aligned} \gamma &= \frac{V_c}{V_a} \\ &= \frac{(1 + \tau) \frac{I_{cell}}{2F \rho_{H_2O}} 10^{-3} M_{H_2O} t_{pi}}{2n_d \frac{I_{cell}}{2F \rho_{H_2O}} M_{H_2O} t_{pi} 10^{-3} + \left(2n_d^* \frac{\lambda_m}{22} - \tau\right) \frac{I_{cell}}{2F}} \end{aligned} \quad (36)$$

2.3 Proton exchange membrane fuel cell test protocol

In this study, the performance and water transport dynamics of the PEMFC were investigated under a driving cycle developed by Chen et al. (Chen et al. 2018), which follows the New European Driving Cycle (NEDC). The driving cycle represents the relationship between operating current density and time. The load levels fluctuate throughout the cycle to evaluate the dynamic response of fuel cell performance, energy efficiency, and water generation. The load profile applied to the fuel cell for dynamic behavior analysis is illustrated in Fig. 3.

It can be observed that the operating current density fluctuates at relatively low levels, ranging from 0 to 300 mA cm⁻² during the low-load phase of fuel cell operation, which lasts up to 830 s. After 830 s, the fuel cell operates under a higher load condition until the end of the driving cycle test, during which the operating current density increases significantly and reaches a maximum value of 780 mA cm⁻².

Table 1

Input parameters for modeling and simulation of the PEMFC in this study

Parameter	Symbol	Value	Unit	References
Cell activation area	A_{fc}	25	cm ²	Well-know
Operating current density	i_{fc}	0 – 2	A cm ⁻²	Well-know
Operating temperature	T_{fc}	333	K	Well-know
Purge valve closed time	t_{pi}	30	s	Well-know
Membrane thickness	δ_m	3×10^{-3}	cm	(Sinha and Wang 2008)
Faraday's constant	F	96485	C mol ⁻¹	(Musio et al. 2011)
Equivalent weight of the membrane	M_m	0.95	kg mol ⁻¹	(Sinha and Wang 2008)
Membrane density	ρ_m	2×10^{-3}	kg cm ⁻³	(Sinha and Wang 2008)
Activation loss constant value	c_1	10	–	(Pukrushpan, Stefanopoulou, and Peng 2004)
Membrane conductivity constant value	b_2	350	–	(Pukrushpan, Stefanopoulou, and Peng 2004)
Concentration loss constant value	c_3	2	–	(Pukrushpan, Stefanopoulou, and Peng 2004)

2.4 Boundary conditions and input parameters

During the modeling and simulation in this study, the following boundary conditions were made to simplify the model and in accordance with the realistic conditions, as follows:

- The supplied gas is considered the ideal gas.
- The operating temperature, operating pressure, and potential in the fuel cell are identical in all places in fuel cells.
- The catalyst layer is uniform during the coated ink process.
- The degradation of the PEMFC performance was not significant and can be ignored because the operating current density is changed frequently and not at a high load level. In addition, the gas species and permeability of the gas within the fuel cell were ignored during fuel cell operation.

The detailed input parameters of the PEMFC are listed in Table 1 and were employed to validate the model in this study. In this study, the ratio of the net water flux within the membrane to the water flux generated at the cathode side was determined based on the boundary conditions of the PEMFCs. At $z = 0$, the membrane water content was found to be 3.4855. Consequently, the ratio of the net water flux in the membrane to the cathode water generation flux was calculated to be 0.7921.

3. Results and discussion

3.1 Validation of the model

The PEMFC performance was affected significantly by the operating temperature. To verify and evaluate the PEMFC performance, both operating pressures at the anode and cathode were fixed at 1.0 atm, with the cell activation area of 25 cm², and the oxygen gas was supplied at the cathode side. The best operating temperature is 60 to 80 °C (Yakubu et al. 2025), which achieves the optimal performance of PEMFC. When the PEMFC operated under extremely high operating temperatures,

the PEMFC performance declined because the electrical conductivity loss occurred quickly (Okonkwo *et al.* 2021). Additionally, the membrane was dry, which is called dehydration, leading to the reversible performance loss (Xu *et al.* 2022). Moreover, the degradation of the membrane increased. In contrast, when the PEMFC operated under low operating temperature, the catalyst activity was reduced that can cause high impedance in the proton (Song *et al.* 2021), reducing the catalyst layer thickness and mechanical fatigue (Sabawa and Bandarenka 2021; Niu *et al.* 2022). Therefore, the operating temperature of PEMFC was set to 60 °C. The polarization curves and overpotential of the PEMFC at the optimal operating temperature are presented in Fig. 4. It can be seen that when the operating current density increased, the cell voltage decreased owing to an increase in the overpotential of activation voltage loss, ohmic voltage loss, and concentration voltage loss. Additionally, the trend of the polarization curve is in good agreement with the published papers previously (Ozen, Timurkutluk, and Altinisik 2016; Santarelli and Torchio 2007; Rohendi *et al.* 2015; Coppo, Siegel, and Von Spakovsky 2006). Therefore, the model achieved high accuracy.

3.2 Effect of purge valve closed time on water in PEMFC

During PEMFC operation, a purge valve is commonly used to improve gas management, reduce fuel consumption, and enhance electrochemical reactions. By closing the outlet using a solenoid valve, the fuel cell operates in the so-called dead-end mode (DEM), as illustrated in Fig. 5. However, PEMFCs operating under the DEM configuration are prone to water accumulation in the flow field channels, which can lead to performance degradation (Siegel *et al.* 2008; Chevalier *et al.* 2015; Siegel *et al.* 2010; Lee, Kim, and Kim 2009). Therefore, investigating the effect of purge-valve closed time on water accumulation in PEMFCs is both necessary and crucial in this study.

Fig. 6(a) illustrates the water accumulation behavior in the fuel cell under different purge-valve closed times. It can be observed that as the purge-valve closed time increases, the amount of accumulated water in the flow field channels also

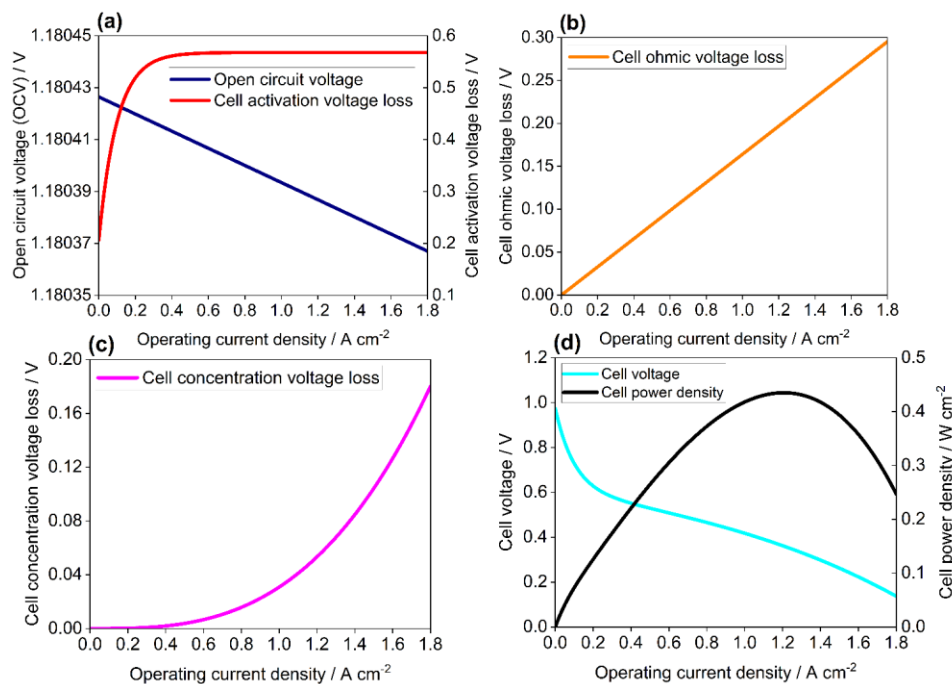


Fig. 4 OCV and cell activation voltage loss (a); Cell ohmic loss (b); Cell concentration voltage loss (c); and cell voltage and power density (d)

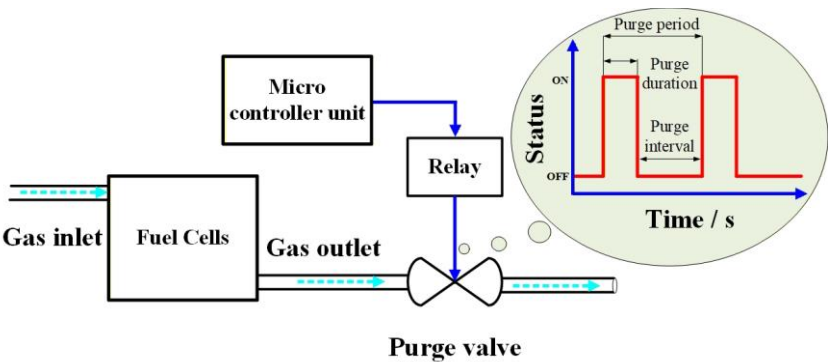


Fig. 5 Dead-end mode configuration in PEMFC

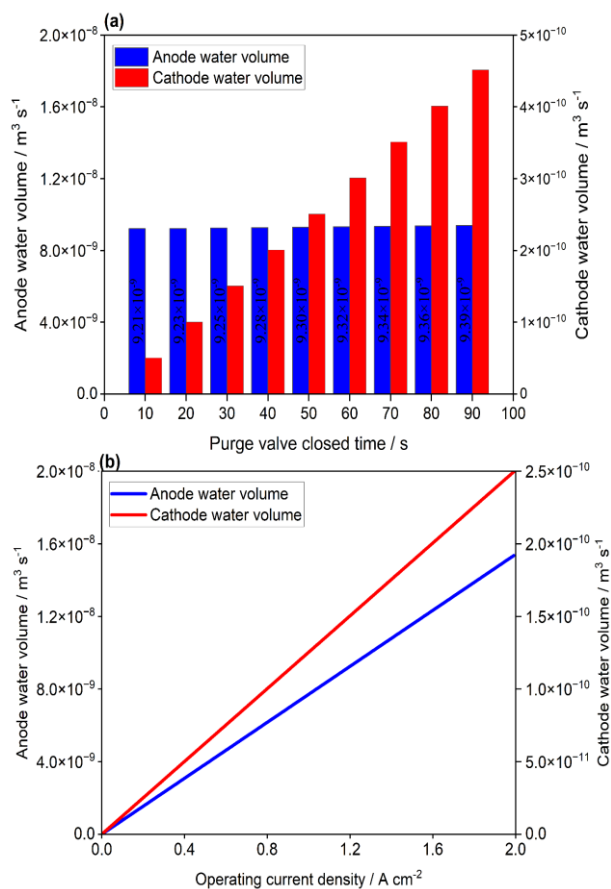


Fig. 6 Anode and cathode water volume under various purge valve closed time (a); and water generation in PEMFC under varying operating current densities (b)

increases. This phenomenon can be attributed to the enhanced electrochemical reactions occurring while the purge valve remains closed, which results in increased water production. Nevertheless, excessive water accumulation leads to performance degradation by reducing the effective active area of the cell and restricting the supply of fresh reactant gases to the flow field channels.

The amount of water generated by the electrochemical reactions at the cathode was higher than that at the anode. This is because the dominant electrochemical reduction reaction occurs at the cathode, where water is produced as a reaction product. Consequently, effective water management and balanced water transport between the anode and cathode sides are necessary and pivotal in this study.

3.3 Effect of load level on water in PEMFC

The water volumes at the anode and cathode sides are influenced by the load level of the fuel cell during operation. Fig. 6(b) illustrates the variation of water volume at the anode and cathode sides under steady-state conditions. It can be observed that the water volume increases in a linear trend as the operating current density increases. This behavior can be attributed to the intensified electrochemical reactions occurring at higher current densities. The detailed values of water volume at the anode and cathode sides under different operating current densities are listed in Table 2.

In practical operation, the cell performance and water volume in a PEMFC vary with dynamic load levels. Therefore, a driving cycle test was employed to evaluate the output voltage of the PEMFC and water accumulation in the flow field channels under realistic operating conditions. Fig. 7(a) illustrates the variation of the output cell voltage under dynamic load levels. It can be observed that the cell voltage fluctuates in response to changes in operating current density. Specifically, an increase in

Table 2
Water volume at the anode and cathode sides under various load levels

Operating current density (A cm^{-2})	Anode side water volume ($\text{m}^3 \text{s}^{-1}$)	Cathode side water volume ($\text{m}^3 \text{s}^{-1}$)
0.2	1.542×10^{-9}	2.507×10^{-11}
0.4	3.084×10^{-9}	5.015×10^{-11}
0.6	4.627×10^{-9}	7.522×10^{-11}
0.8	6.169×10^{-9}	1.003×10^{-10}
1.0	7.711×10^{-9}	1.254×10^{-10}
1.2	9.253×10^{-9}	1.504×10^{-10}
1.4	1.080×10^{-8}	1.755×10^{-10}
1.5	1.157×10^{-8}	1.881×10^{-10}

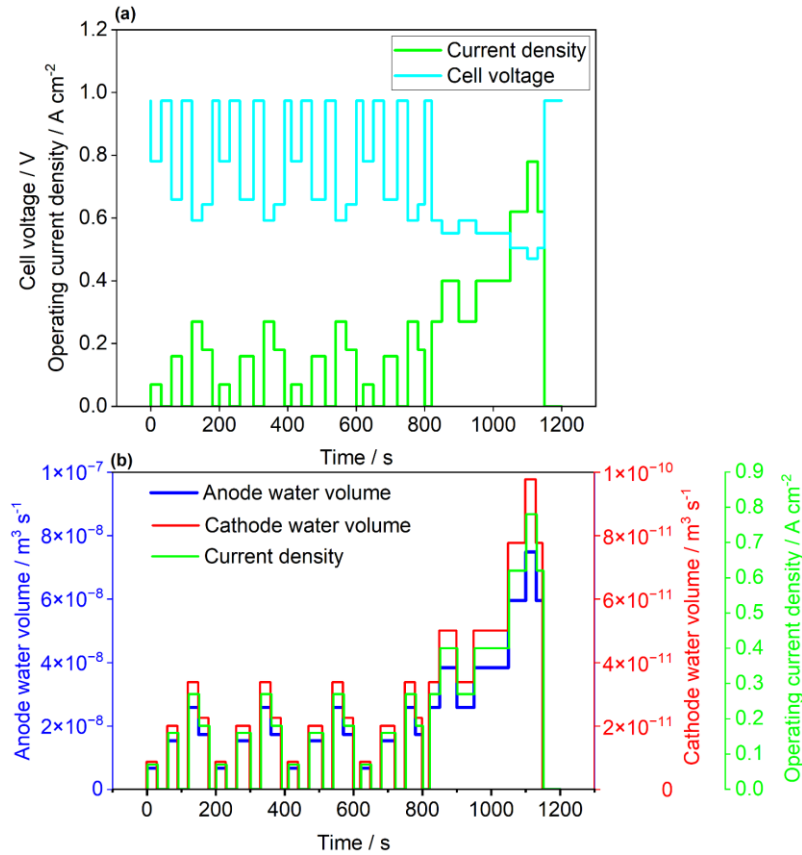


Fig. 7 Dynamic cell performance under driving cycle test (a); and water generation at the anode and cathode side under dynamic loads (b)

operating current density leads to a decrease in output voltage, and vice versa. This behavior can be attributed to increased water generation and accumulation at higher load levels, which may induce flooding in the flow field channels. Consequently, the effective active area of the cell is reduced, restricting the supply of reactant gases and leading to a decline in cell performance.

Fig. 7(b) illustrates the water volume dynamics at both the anode and cathode sides under varying load levels. It can be observed that as the load level increases, the water volumes at the anode and cathode sides increase due to intensified electrochemical reactions, resulting in greater water production

within the fuel cell. Conversely, during low load levels, the water volumes decrease owing to weaker electrochemical reactions. At the highest operating current density of 0.78 A cm⁻², the anode and cathode water generation were achieved at 7.491×10^{-8} and 9.779×10^{-11} m³ s⁻¹, respectively.

3.4 Effect of water content in the membrane on water in PEMFC

During PEMFC operation, the water content in the membrane significantly influences water generation within the fuel cell due to its contribution to electrochemical reactions and humidity regulation. Figure 8 presents the variation in water generation

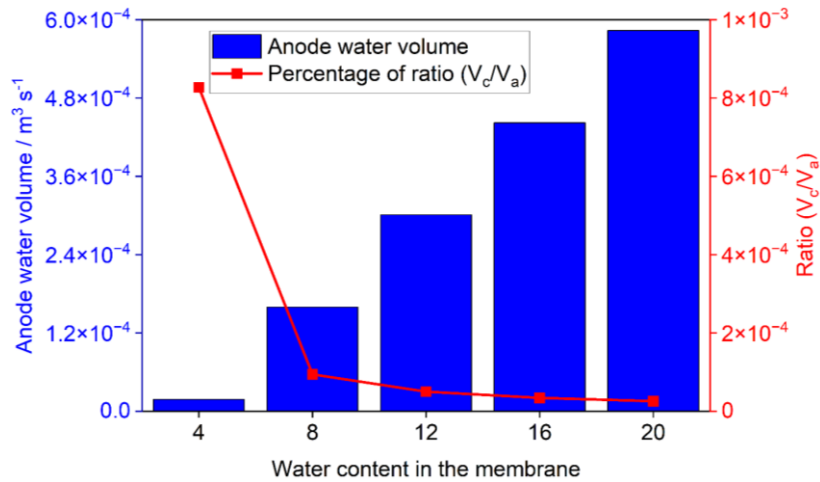


Fig. 8 Effect of water content on water generation and the percentage of the ratio of cathode water volume to the anode water volume

and the ratio of cathode water volume to anode water volume in this study. It can be observed that as the membrane water content increases, water generation at the anode side also increases, owing to enhanced humidification. Furthermore, with increasing water content, the ratio of cathode water volume to anode water volume gradually decreases. This behavior can be attributed to the increasing water volume at the anode side, which leads to a reduction in the ratio. When the fuel cell operates at high membrane water content, excessive anode-side water accumulation may occur, potentially causing flooding within the fuel cell. Therefore, effective water management plays a crucial role in achieving high PEMFC performance. At the high water content, the anode water volume and ratio of the cathode water volume and anode water volume were obtained $5.835 \times 10^{-4} \text{ m}^3 \text{ s}^{-1}$ and $2.578 \times 10^{-5}\%$, respectively.

3.5 Optimization of water management strategy in PEMFC

In this study, the optimal power density of the fuel cell was achieved at 0.435 W cm^{-2} with an operating current density of 1.2 A cm^{-2} . Accordingly, water management optimization in the PEMFC was proposed at this operating point to maintain the highest cell performance. Water transport within the fuel cell is highly complex and presents significant challenges during PEMFC operation. Therefore, the development of an effective water management strategy is necessary and plays a crucial role in achieving the maximum power density.

The proposed water management strategy was optimized based on the ratio of cathode water volume to anode water volume. In this study, the optimal ratio was determined to be 1.63%. In other words, when the cathode water volume accounts for 1.63% of the anode water volume, a suitable water balance is achieved within the fuel cell. This ratio provides sufficient membrane humidification to prevent dehydration while avoiding excessive water accumulation, thereby enabling the highest cell performance.

Fig. 9 illustrates the cell performance together with the anode and cathode water volume rates under different operating current densities. It can be observed that as the operating current density increases, the water volume increases significantly due to intensified electrochemical reactions. At the

point of maximum power density, the water content is well balanced, enabling the highest cell performance. However, when the operating current density exceeds 1.2 A cm^{-2} , cell performance declines due to excessive water accumulation, which can induce flooding in the PEMFC. This flooding reduces the effective active area of the cell and restricts the supply of fresh reactant gases to the flow field channels, ultimately resulting in degraded cell performance. Therefore, optimizing the water management strategy is both insightful and essential for enhancing PEMFC performance.

4. Conclusions

In this study, a PEMFC performance model was developed, and an optimization strategy was proposed to enhance cell performance by considering water transport within the PEMFC. Several conclusions can be drawn in this study. Indeed, the cell performance decreases with increasing operating current density due to higher overpotentials and excessive water accumulation. The dynamic water transport model was developed to capture the mobility and accumulation of water at both the anode and cathode sides. As the operating current density increases, water generation also increases due to intensified electrochemical reactions in the PEMFC. In addition, the dynamic behavior of PEMFC performance and water generation under varying load levels was investigated using a driving cycle test. Furthermore, the water management optimization strategy was proposed to achieve maximum cell power. The optimal ratio of cathode water volume to anode water volume was determined to be 1.63%. By proposing a water management optimization strategy under maximum power operating conditions, the developed model can be applied to engineering applications utilizing PEMFC power sources, such as tramways, electric vehicles, portable power systems, and stationary power generation systems. Furthermore, the PEMFC control system can monitor performance based on the proposed ratio of cathode water volume to anode water volume, thereby enhancing water management and system stability. This study provides meaningful insights into optimizing PEMFC performance by accounting for the dynamic behavior of water transport within the fuel cell.

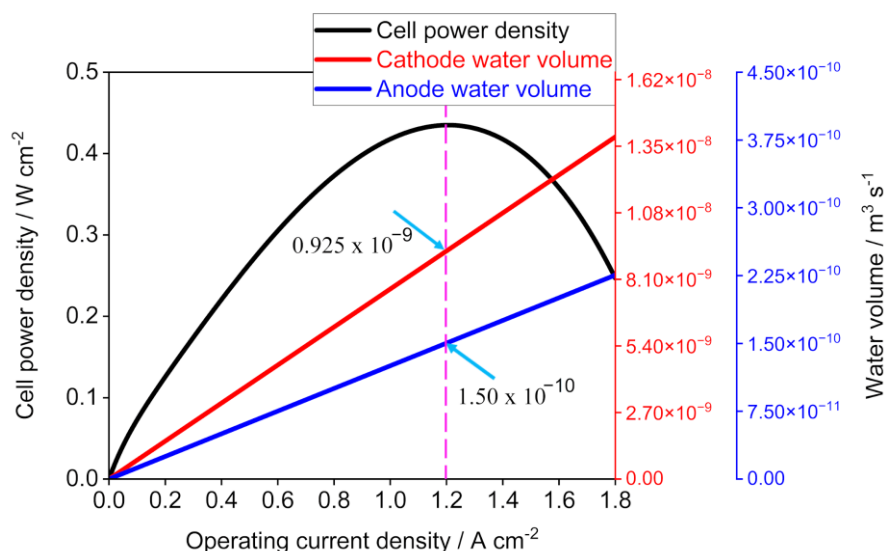


Fig. 9 Optimization of water management for PEMFC in this study

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Author Contributions: T.T.D.: Conceptualization, methodology, formal analysis, writing—original draft, supervision, resources, project administration, writing—review and editing, project administration, validation. Author have read and agreed to the published version of the manuscript.

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