

© 2025 This manuscript version is made available under the CC-BY-NC-ND 4.0 license <https://creativecommons.org/licenses/by-nc-nd/4.0/>

The definitive publisher version is available online at <https://doi.org/10.1016/j.ijhydene.2025.02.238>

Study on Cold-Start Macro- and Micro-Performance of a Proton Exchange Membrane Fuel Cell using a Novel Quasi-Two-Dimensional Dynamic Model

Shengping Li ^{a, 1}, Huali Zhao ^{a, 1}, Hongyuan Ding ^b, Yuhan Huang ^c,
Chunhui Wang ^d, Jiyan Wei ^{a, e}, Zhaowen Wang ^{a *}

^a School of Energy and Power Engineering, Huazhong University of Science and Technology, Wuhan, 430074, China

^b Wuhan Second Ship Design and Research Institute, Wuhan, 430064, China

^c Centre for Green Technology, School of Civil and Environmental Engineering, University of Technology Sydney, NSW
2007, Australia

^d National Key Laboratory of Marine Engine Science and Technology, Shanghai, 201108, China

^e Hubei Key Laboratory of Advanced Technology for Automotive Components, Wuhan University of Technology, Wuhan
430070, China

* Corresponding authors.

E-mail address: wangzhaowen@hust.edu.cn (Z. Wang).

¹ Equal contribution.

Abstract

Cold start is one of the key challenges impeding the popularization of the proton exchange membrane fuel cells (PEMFCs), and icing is a major reason hindering cold starts. This paper developed a new Quasi-two-dimensional model to explore the macro- and micro-performance of PEMFCs cold start. Especially, the spatial-temporal distribution of internal temperature, phase change of water, and effects of different assisted heating methods were comprehensively analyzed based on various cold-start heating strategy. The results showed that, at the low temperature of 253 K, as PEMFCs cold starts, the cathode generated water and solid ice forms in the cathode catalyst layer rapidly, especially under higher starting current density because of much rich water generation. Icing then progressively extended to the cathode gas diffusion layer and the proton exchange membrane and filled the pores. While the proton exchange membrane had less icing because of membrane-bound water form. When the ice content in the cathode catalyst layer reached 98%, the mass transport and reaction in the PEMFCs were hindered and the successful cold start became significantly challenging. Coupling the adjustable coolant-assisted heating method (0-25 W) and the step-slope current variation enabled suitable cold start under ultra-low-temperature environments. With auxiliary heating, ice content in catalytic layer first increased rapidly although the temperature in the cathode catalytic layer increased to 263 K in about 5 s. Ice started to melt till temperature reach 274 K with continues heating, and the highest ice content 2.2% was remained. Under the weak icing progress, the fuel cell cold-started successfully within 15 s.

Keywords: Proton exchange membrane fuel cell; Quasi-two-dimensional model; Low-temperature cold start; phase change mechanism; Coolant assisted heating

1 Introduction

Proton exchange membrane fuel cells (PEMFCs) are widely considered as the main power source of road transport because of their advantages of low operating temperature, high conversion efficiency, and zero pollution [1-3]. However, icing occurred during cold start at low temperatures, which could seriously affect the mass transfer inside the PEMFCs [4, 5]. The effect of icing on the startup hindered the development and popularization of PEMFCs [6]. Therefore, the internal changes and startup strategized of PEMFCs in cold start under low temperature environment have attracted much attention of researchers.

Many studies have investigated the PEMFC cold start performance at low temperatures [7, 8]. Ice generation and development during PEMFC cold operation were difficult to be observed by experiments, where numerical methods became more feasible and economic for the design and optimization of PEMFC cold starts [9]. Xu et al. [10] developed a pore-scale 3D model to explore the heat transfer and flow processes during cold start. They found that increasing the content of platinum could effectively accelerate the melting of ice. Similarly, Macedo et al. [11] developed a 3D model to analyze the temperature distribution of the stack during cold start. They reported that higher temperatures were shown at the ribs of the cathode and near the flow outlet. Niu et al. [12] demonstrated that the initial water content of the proton membrane was the most sensitive to the cold start process. Meanwhile, Wei et al. [13] also emphasized the critical impact of inflow uniformity on the performance of PEMFC cold start.

Various strategies have been proposed to improve the success rate and performance of PEMFC cold start at low temperatures. Pan et al. [14] proposed an adaptive cold-start strategy and showed that the best overall performance was achieved with a cold-start time of 360 s. Lei et al. [15] pointed out that different current loading modes led to different effects on cold start. Further, Liu et al. [16] argued that a constant slope current loading mode was more favorable for fast start-up in stacks with coolant recirculation. Gießgen et al. [17] developed a 2D transient physical model with a thermochemical preheater, which advanced the time of successful cold start to 23 s at 253 K by an assisted start strategy. Tsai et al. [18] developed an anode dead-end fuel cell model for comparative analysis of cold-start strategies, and showed that the optimal purge duration was about 0.1 s using a voltage-drop strategy. Rajbongshi et al. [19] achieved a successful cold start using low-temperature gas purging and suggested that the cold-start performance decay varied according to different starting temperatures. Wang et al. [20] found that the temperature difference between cells of a stack during cold start could be up to 10 K. However, increasing the cathode gas flow rate could effectively avoid cold start failure.

Chang et al. [21] analyzed the PEMFC start performance at extremely low temperatures (253 K), and suggested that the cold-start performance could be further improved in terms of flow field and materials. Various optimization strategies were developed in terms of PEMFC structure [22-25]. García-Salaberri et al. [26] developed a multiscale PEMFC model for parametric analysis, and concluded that adjusting the electrode plate size and gas diffusion layer (GDL) thickness could greatly improve the cold-start performance. A 3D multiphase model was developed to optimize the cold-start process of a PEMFC [27]. It was found that increasing the proportion of polymer in the cathode catalytic layer (CL) could reduce the ice formation more significantly. Yang et al. [28] found that a single-channel serpentine flow field provided a superior performance and dynamic response. Lin et al. [29] investigated the effect of optimized microporous layer (MPL) on the cold start process by a segmented cell technique. They reported that the optimized stack could achieve unassisted cold start at 253 K. Dafalla et al. [30] designed a method of anode channel blockage which could effectively improve the

cold start performance.

PEMFC optimization and performance prediction based on data-driven are gaining significant attention recently [31-33]. Zhang et al. [34] proposed a real-time prediction method based on the remaining cold start time and showed that the accuracy of the model was greatly improved with an average error of only 3 s. A data-driven PEMFC cold-start model was developed to improve the computational efficiency [35]. The model-optimized cold-start strategy could reduce the startup time by 26 s at 243 K. Liu et al. [36] analyzed the distribution of ice during the PEMFC cold start with different parameters and improved the cell cold start performance by an optimization algorithm.

While assisted heating has been recognized as a simple yet effective approach to address cold start challenges [37, 38], the relationship between the temperature variation and the ice evolution pattern in the fuel cell cathode catalytic layer had less been described. Meanwhile, the studies of cold start performance by coupled external heating method and step-slope current variation were still erratic. Therefore, it is necessary to deeply analyze the intrinsic evolution of the temperature distribution, water distribution and icing progress during the cold-start process under various cold-start strategy, and then an effective cold-start strategy is released to further the progress of PEMFCs industry.

To address these challenges, this paper developed a novel quasi-2D dynamic model based on MATLAB Simulink by optimizing the heat transfer algorithm between the PEMFCs and the external environment. This model enabled a comprehensive investigation of both macroscopic and microscopic cold-start performance under various assisted heating strategies, including thermostatic intake heating, thermostatic coolant heating, and variable power coolant heating. This paper deeply analyzed the internal water, ice and temperature distribution characteristics, as well as the dynamic response performance under different cold-start strategies. especially focused on the spatial-temporal evolution patterns of internal water and the effect to cold start. Further, a new cold-start strategy coupled with assisted heating and a step-slope current variation was adopted to optimize the cold start performance of PEMFCs.

2 Methodology

A quasi-two-dimensional dynamic model of PEMFC is developed based on MATLAB Simulink, as shown in **Fig. 1**. To effectively find the better startup strategy for PEMFC cold start, the research object of this paper is a single cell. The model includes calculation modules of material transport, flow channel component, porous layer component, voltage, temperature distribution, and variable operating condition realization. In the temperature calculations, the heat exchange between the fuel cell and environment cannot be neglected. The effect of coolant and intake gas on the temperature of the fuel cell during this process is also fully considered and the localized heat transfer sub-model is updated. It is possible to efficiently calculate the voltage output of a single cell at low temperatures as well as the distribution of temperature, fuel, water, and ice in the cell.

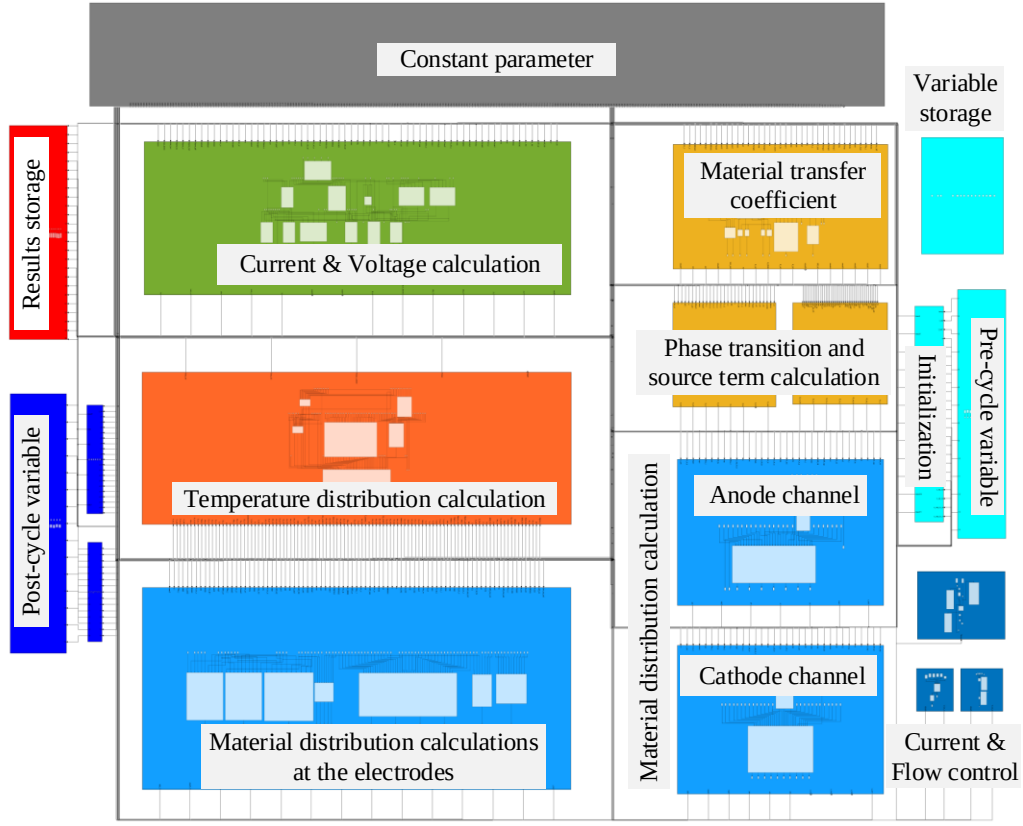


Fig. 1. A quasi-two-dimensional model of PEMFC.

2.1 Mathematical model

2.1.1 Material distribution model

The control equations of the PEMFC quasi-two-dimensional model are based on the principles of electrochemical reaction, mass conservation and energy conservation. The gas component control equation is expressed as:

$$\frac{\partial((1-s_{lq}-s_{ice})\rho_g Y_i)}{\partial t} + \frac{\partial(\rho_g u_g Y_i)}{\partial x} = \nabla \cdot (\rho_g D_i^{\text{eff}} Y_i) + S_i \quad (1)$$

The four terms from the left to the right hand side are the substance component change, inlet (0 in the internal porous layer and proton exchange membrane), gas diffusion and gas source terms, respectively. s_{lq} is the liquid water volume fraction in the pores, s_{ice} is the volume fraction of ice, and Y_i is the mole fraction of gas i . The above parameters are from the simulation calculation process. t is the running time, x is the gas flow distance, ρ_g is the density of gas i , u_g is the flow rate of gas, and D_i^{eff} is the effective diffusion coefficient of the gas which can be calculated as:

$$D_i^{\text{eff}} = \begin{cases} D_i (1-s_{lq}-s_{ice})^{1.5} \varepsilon^{1.5} & (\text{in porous zones}) \\ Sh D_i & (\text{in CH}) \end{cases} \quad (2)$$

where D_i is the diffusion coefficient of gas (O_2 , H_2 , N_2 , VP), and Sh is the Sherwood number ($Sh=2.3$), ε is the porosity (**Table 1**).

In the catalytic layer and the proton exchange membrane, a portion of the water combines with sulfonic acid groups to form membrane water. The transport and phase transition processes of membrane water are quite different from that of liquid and water vapor. The existence of membrane water is crucial for fuel cell performance, whose control equation is:

$$\frac{\rho_{\text{Mem}}}{EW} \frac{\partial(\omega \lambda_{\text{mw}})}{\partial t} = \frac{\rho_{\text{Mem}}}{EW} \nabla \cdot (\omega^{1.5} D_{\text{mw}} \lambda_{\text{mw}}) + S_{\text{mw}} \quad (3)$$

The three terms from the left to right hand side are the membrane water change, diffusion and source, respectively. λ_{mw} is the membrane water content from the calculations, ω is the volume fraction of polymer in the catalytic layer (0.4), S_{mw} is the membrane water source term, and D_{mw} is the membrane water diffusion coefficient which is calculated as:

$$D_{\text{mw}} = \begin{cases} 3.1 \times 10^{-7} \lambda_{\text{mw}} [\exp(0.28 \lambda_{\text{mw}}) - 1] \exp(-2346/T) & (0 < \lambda_{\text{mw}} < 3) \\ 4.17 \times 10^{-8} \lambda_{\text{mw}} [161 \times \exp(-\lambda_{\text{mw}}) + 1] \exp(-2346/T) & (3 \leq \lambda_{\text{mw}} < 17) \end{cases} \quad [39] \quad (4)$$

The membrane water source term S_{mw} consists of a phase transition source term, an electrochemical reaction source term, and an electrical drag source term. T is the temperature of the fuel cell.

The control equation for liquid water based on the hydraulic continuum phenomenon is expressed as:

$$\frac{\partial(\varepsilon \rho_{\text{liq}} S_{\text{liq}})}{\partial t} = \nabla \cdot \left(\rho_{\text{liq}} \frac{K_{\text{liq}}}{\mu_{\text{liq}}} p_{\text{liq}} \right) + S_{\text{liq}} \quad (5)$$

$$\mu_{\text{liq}} = 2.414 \times 10^{-5} \times 10^{247.8/(T-140)} \quad (6)$$

The three terms from the left to right hand side in Eq. (5) is the change, permeability and source of liquid water, respectively. ρ_{liq} (1000 kg m⁻³) is the density of liquid water, K_{liq} is the permeability of liquid water (**Table 1**), μ_{liq} (kg m⁻¹ s⁻¹) is the dynamic viscosity of the liquid, p_{liq} is the liquid pressure.

The ice phase control equation has no permeability term and is expressed as:

$$\frac{\partial(\varepsilon \rho_{\text{ice}} S_{\text{ice}})}{\partial t} = S_{\text{ice}} \quad (7)$$

Table 1. Model parameters [39].

Parameters	Values	Parameters	Values
Activation area, A_{act}	25e ⁻⁴ m ²	Permeability in gas diffusion layer, $K_{\text{liq,GDL}}$	10e ⁻¹²
Porosity of gas diffusion layer, ε_{GDL}	0.6	Permeability in microporous layer, $K_{\text{liq,MPL}}$	10e ⁻¹³
Porosity of microporous layer, ε_{MPL}	0.4	Permeability in catalytic layer, $K_{\text{liq,CL}}$	10e ⁻¹⁴
Porosity of catalytic layer, ε_{CL}	0.3	Conductivity of bipolar plate, σ_{BP}	2e ⁴ S m ⁻¹
Thickness of bipolar plate, δ_{BP}	0.005 m	Conductivity of gas diffusion layer, σ_{GDL}	5000 S m ⁻¹
Thickness of gas diffusion layer, δ_{GDL}	3e ⁻⁴ m	Conductivity of microporous layer, σ_{MPL}	5000 S m ⁻¹
Thickness of the microporous layer, δ_{MPL}	4e ⁻⁵ m	Conductivity of catalytic layer, σ_{CL}	5000 S m ⁻¹
Thickness of catalytic layer, δ_{CL}	10e ⁻⁶ m	Thermal conductivity of bipolar plate, k_{BP}	20 W m ⁻¹ K ⁻¹
Specific heat capacity of bipolar plate, Cp_{BP}	1580 J kg ⁻¹ K ⁻¹	Thermal conductivity of solids, k_s	1 W m ⁻¹ K ⁻¹
Density of bipolar plate, ρ_{BP}	1000 kg m ⁻³	Thermal conductivity of membrane, k_{MEM}	0.95 W m ⁻¹ K ⁻¹

Specific heat capacity of gas diffusion layer, Cp_{GDL}	2000 J kg ⁻¹ K ⁻¹	Thermal conductivity of anode gas, $k_{g,a}$	0.17 W m ⁻¹ K ⁻¹
Density of gas diffusion layer, ρ_{GDL}	1000 kg m ⁻³	Thermal conductivity of cathode gas, $k_{g,c}$	0.024 W m ⁻¹ K ⁻¹
Specific heat capacity of microporous layer, Cp_{MPL}	568 J kg ⁻¹ K ⁻¹	Specific heat capacity of membrane, Cp_{MEM}	833 J kg ⁻¹ K ⁻¹
The density of microporous layer, ρ_{MPL}	1000 kg m ⁻³	Density of membrane, ρ_{MEM}	1980 kg m ⁻³
Specific heat capacity of catalytic layer, Cp_{CL}	3300 J kg ⁻¹ K ⁻¹	Density of catalytic layer, ρ_{CL}	1000 kg m ⁻³

2.1.2 Electrochemical model

The single-cell output voltage of PEMFC can be calculated according to the mutual balance between chemical and electric energies in the reactants:

$$V_{out} = V_{nernst} + \eta_{act,a} + \eta_{act,c} + \eta_{conc,a} + \eta_{conc,c} + \eta_{ohmic} \quad (8)$$

where V_{out} is the monolithic output voltage, V_{nernst} is the Nernst voltage, $\eta_{act,a}$ and $\eta_{act,c}$ are the anodic and cathodic activation polarization loss electromotive forces, respectively, η_{ohmic} is the ohmic polarization loss electromotive force, $\eta_{conc,a}$ and $\eta_{conc,c}$ are the concentration polarization loss electromotive force. As a reversible electrochemical voltage, V_{nernst} is affected by the concentration of the substance and the gas pressure:

$$V_{nernst} = \left(\Delta G - \frac{T\Delta S}{nF} \right) + \frac{RT}{nF} \ln \frac{P_{H_2} P_{O_2}^{0.5}}{P_{H_2O}} \quad (9)$$

where F is the Faraday constant (96483 C mol⁻¹), ΔG is the Gibbs free energy (-273.145 kJ mol⁻¹), ΔS is the standard molar entropy change (-163.29 kJ mol⁻¹ K⁻¹), R is the ideal gas constant (8.314 J kg⁻¹ K⁻¹), p_{H_2} is the anodic hydrogen partial pressure, and p_{O_2} is the cathodic oxygen partial pressure which can be determined from calculations. The activation polarization loss electric potentials are given as:

$$\eta_{act,a} = \frac{RT}{2\alpha F} \ln \frac{I}{j_a + j_{leak}}, \quad \eta_{act,c} = \frac{RT}{4\alpha F} \ln \frac{I}{j_c + j_{leak}} \quad (10)$$

where α is the charge transfer coefficient ($\alpha=0.5$), I is the current density which is under external control, j_{leak} is the leakage current, and $j_{a/c}$ is the exchange current density which is calculated as [39]:

$$j_a = j_{0,a}^{ref} (1 - s_{lq} - s_{ice}) \left(\frac{p_{H_2}}{p_{H_2}^{ref}} \right)^\gamma \exp \left[-b_a \left(1 - \frac{T}{298.15} \right) \right] \quad (11)$$

$$j_c = j_{0,c}^{ref} (1 - s_{lq} - s_{ice}) \left(\frac{p_{O_2}}{p_{O_2}^{ref}} \right)^\gamma \exp \left[-b_c \left(1 - \frac{T}{298.15} \right) \right] \quad (12)$$

where $j_{0,a}^{ref}$ and $j_{0,c}^{ref}$ denote the reference exchange current densities per unit catalyst surface of anode and cathode, respective, γ is pressure coefficient (in this case, $\gamma=1$), b is the calculation coefficient ($b_a=1400$, $b_c=7900$), p_r^{ref} is the reference pressure. s_{lq} and s_{ice} are the volume fraction of water and ice, respectively. The leakage current j_{leak} is calculated as:

$$j_{\text{leak}} = \begin{cases} \frac{2FJ_{\text{H}_2, \text{cross}}}{\delta_{\text{CLc}}} & (\text{Cathode}) \\ \frac{4FJ_{\text{O}_2, \text{cross}}}{\delta_{\text{CLa}}} & (\text{Anode}) \end{cases} \quad (13)$$

The ohmic loss electromotive force is caused by the resistance to proton transfer, electrodes and end plates to electron transfer. So, the voltage drop due to ohmic loss is proportional to the current density and can be calculated as:

$$\eta_{\text{ohmic}} = -(\sum ASR)I = -\left(\frac{\delta_{\text{BP}}}{\sigma_{\text{BP}}} + \frac{\delta_{\text{GDL}}}{\sigma_{\text{s, GDL}}} + \frac{\delta_{\text{MPL}}}{\sigma_{\text{s, MPL}}} + \frac{\delta_{\text{CL}}}{2\sigma_{\text{s, CL}}} + \frac{\delta_{\text{MEM}}}{\sigma_{\text{MEM}}}\right)I \quad (14)$$

where δ is the thickness of each layer, σ is the conductivity of each layer, and σ_{MEM} is the conductivity of the proton exchange membrane which is calculated as [40, 41]:

$$\sigma_{\text{MEM}} = 0.001(5.139\lambda_{\text{eq}} - 3.26)\exp\left[1268\left(\frac{1}{303} - \frac{1}{T}\right)\right] \quad (15)$$

$$\lambda_{\text{eq}} = \begin{cases} 0.043 + 17.81a - 39.85a^2 + 36a^3 & (0 < a < 1) \\ 14 + 1.4(a - 1) & (1 \leq a) \end{cases} \quad (16)$$

$$a = \frac{p_{\text{vp}}}{p_{\text{sat}}} \quad (17)$$

where λ_{eq} is the equilibrium water content, a is the water vapor activity and p_{vp} is the water vapor partial pressure determined from calculations.

The concentration polarization loss is caused by the consumption of reactants involved in the electrochemical reaction, resulting in a decrease in concentration. It is the main reason for the rapid decrease in voltage at high current density and can be calculated as:

$$\eta_{\text{conc, a}} = \frac{RT}{2\alpha_a F} \ln\left(1 - \frac{I}{I_{\text{lim, a}}}\right), \eta_{\text{conc, c}} = \frac{RT}{4\alpha_c F} \ln\left(1 - \frac{I}{I_{\text{lim, c}}}\right) \quad (18)$$

$$I_{\text{lim, a}} = \frac{2Fc_{\text{H}_2, \text{CH}}}{\frac{\delta_{\text{CL}}}{2D_{\text{H}_2, \text{CL}}^{\text{eff}}} + \frac{\delta_{\text{MPL}}}{D_{\text{H}_2, \text{MPL}}^{\text{eff}}} + \frac{\delta_{\text{GDL}}}{2D_{\text{H}_2, \text{GDL}}^{\text{eff}}}} \quad (19)$$

$$I_{\text{lim, c}} = \frac{4Fc_{\text{O}_2, \text{CH}}}{\frac{\delta_{\text{CL}}}{2D_{\text{O}_2, \text{CL}}^{\text{eff}}} + \frac{\delta_{\text{MPL}}}{D_{\text{O}_2, \text{MPL}}^{\text{eff}}} + \frac{\delta_{\text{GDL}}}{2D_{\text{O}_2, \text{GDL}}^{\text{eff}}}} \quad (20)$$

where I_{lim} refers to the limiting current density of the cathode and anode, $D_{\text{i, CL}}^{\text{eff}}$, $D_{\text{i, MPL}}^{\text{eff}}$, and $D_{\text{i, GDL}}^{\text{eff}}$ refer to the effective localized gas diffusion coefficient, and $c_{\text{i, CH}}$ is the molar concentration of the gas at the channel from the simulations.

2.1.3 Temperature distribution model

The control equation of temperature distribution is:

$$\frac{\partial((\rho C_p)^{\text{eff}} T)}{\partial t} = \nabla \cdot (k_T^{\text{eff}} \nabla T) + S_T \quad (21)$$

The three terms from the left to right hand side are the temperature change term, the thermal transfer term, and the thermal source term, respectively. $(\rho C_p)^{\text{eff}}$ is the equivalent specific heat capacity, k_T^{eff} is the equivalent thermal conductivity.

The equivalent specific heat capacity $(\rho C_p)^{\text{eff}}$ can be calculated as:

$$(\rho C_p)^{\text{eff}} = \varepsilon \left[(s \rho C_p)_{\text{liq}} + (s \rho C_p)_{\text{ice}} + (1 - s_{\text{ice}} - s_{\text{liq}})(\rho C_p)_g \right] + (1 - \varepsilon - \omega)(\rho C_p)_s + \omega(\rho C_p)_{\text{MEM}} \quad (22)$$

where s_i is the volume fraction of the different components, $C_{p,i}$ is the density of the different components, J is the specific heat capacity of the different components and ω (0.4) is the polymer volume fraction. These parameters are listed in Table 1. The equivalent thermal conductivity k_T^{eff} is calculated as:

$$k_T^{\text{eff}} = \varepsilon \left[s_{\text{liq}} k_{\text{liq}} + s_{\text{ice}} k_{\text{ice}} + (1 - s_{\text{ice}} - s_{\text{liq}}) k_g \right] + (1 - \varepsilon - \omega) k_s + \omega k_{\text{MEM}} \quad (23)$$

where k is the local thermal conductivity. In a stack, the surface of a single cell, the coolant and the intake gas all exchange heat with the environment, which in turn has an impact on the temperature distribution inside the cell.

Therefore the heat exchange calculation is optimized and a computational factor is added. The heat exchange between the fuel cell and the environment can be expressed as:

$$Q = \zeta h (T_{\text{en}} - T_{\text{BP}}) A_{\text{BP}} \quad (24)$$

where Q is the amount of heat exchanged between the fuel cell and the environment, ζ is the heat transfer correction factor (0.015) which was calculated based on the heat exchange between a single cell and the environment in the conceptual stack model, h is the heat transfer coefficient (20 W m² K⁻¹), T_{en} is the environmental temperature, T_{BP} is the temperature of the fuel cell bipolar plate, and A_{BP} is the area of the bipolar plate heat transfer (assuming that $A_{\text{BP}} = A_{\text{cell}} = 0.0001 \text{ m}^2$).

2.2 Boundary conditions

In the simulation, the inlet pressures at the anode and cathode sides were both set to 150 kPa. Intake gas relative humidity (RH) of cathode and anode were set to 0% and 70%, respectively. Hydrogen and air were in a counter-flow mode. The stoichiometric ratios of hydrogen and air were 1.2 and 2.0, respectively. The environmental temperature was set to 253 K. **Table 1** gives the parameters used in the PEMFC cold start model. Three heating-assisted cold start methods were considered in this study, i.e., constant temperature intake-assisted heating, constant temperature coolant heating, and adjustable coolant heating. The first two methods used cathode-anode intake air and coolant of constant temperatures (i.e., 263, 273 and 283 K) to directly heat the fuel cell, respectively. The third method utilized a pulse heating power to heat the coolant to indirectly heat the fuel cell.

2.3 Assumptions

To simplify the calculations, the following assumptions are made for the quasi-two-dimensional model:

- (1) In this model, natural convection driven by gravity is weaker in the vertical direction, so the effects of gravity

are ignored in the calculation of fuel and water transport in porous media;

- (2) The gas flow in the flow channel is considered to be laminar due to the small Reynolds number;
- (3) Convective transport of gases in any direction in porous media is negligible due to the way diffusion dominates material transport;
- (4) Liquid water is blown away quickly by the gas in the flow channel, so the liquid water volume fraction in the flow channel is assumed to be zero;
- (5) The conductivity of the polar plates is high, so the potential distribution on the polar plates is uniform, and it is assumed that the contact resistance at the interface between the polar plates and the diffusion layer is negligible;
- (6) Pressure is unchanged in the flow channel due to the low inlet flow rate and the short flow path.

2.4 Model verification

To verify the model, the simulation results were compared against the experimental data in Ref [42] at environment temperatures of 270 and 253 K. The stability of the model is further compared for different numbers of model nodes (i.e., $N=5$ and 10). As shown in **Fig. 2**, the simulation results agree well with the experimental data under 273 K and start-up current density (I_{start}) of 0.04 A/cm^2 . The maximum error is 1.8% under 253 K and 0.1 A/cm^2 , which meets the engineering requirements. This maximum error occurs in the case of the initial membrane state water content $\lambda = 3.4$. This is mainly because the effect of membrane state water and its icing on the performance of the fuel cell are more sensitive in the model than in practice. **Fig. 2** also shows that there is insignificant difference between $N=5$ and $N=10$, indicating that a stable accuracy of the model. Therefore, this study adopted $N=5$ model nodes to save computational time.

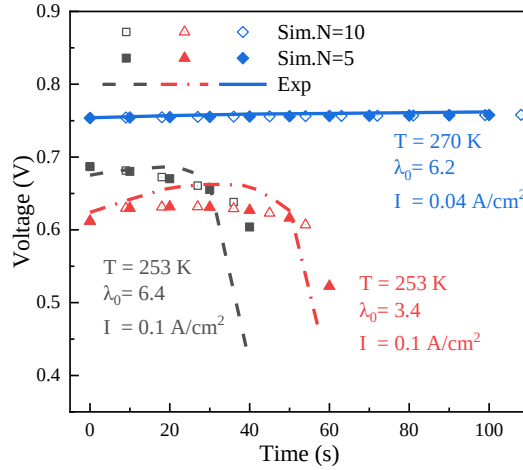


Fig. 2. Verification of quasi-two-dimensional models under different operating conditions.

3 Results and discussion

3.1 Dynamic performance of low-temperature self-starting

The effect of constant current densities on the self-starting performance of PEMFC is studied. **Fig. 3** shows the fuel cell polarization curves at different starting current densities. As the current density increases, fuel cell start-up failures happen substantially earlier. When $I_{\text{start}} = 0.1 \text{ A/cm}^2$, the fuel cell startup failure occurs at about 38 s. However, the startup failure was advanced to 7 s at $I_{\text{start}} = 0.6 \text{ A/cm}^2$. Also, the rate of fuel cell voltage reduction increases rapidly as the current

density increases. This is mainly because the rate of electrochemical reaction increases with current density, producing more water. However, the temperature of the fuel cell is still below freezing, so it will rapidly freeze and thus increase the resistance to ion transport. Thus, it is predictable that fuel cell cold starts are easier to maintain at low current densities. In contrast, the cold start fails quickly at high current densities ($I_{\text{start}} \geq 0.6 \text{ A/cm}^2$) and is therefore less feasible. In addition, at the beginning of startup, the voltage rises briefly and then drops rapidly. The higher the starting current density, the more obvious this trend is. This is mainly because higher current densities at the beginning of startup increase the cell temperature and thus the electrochemical reaction rate more dramatically. Consequently, this voltage increase is more significant at higher current densities.

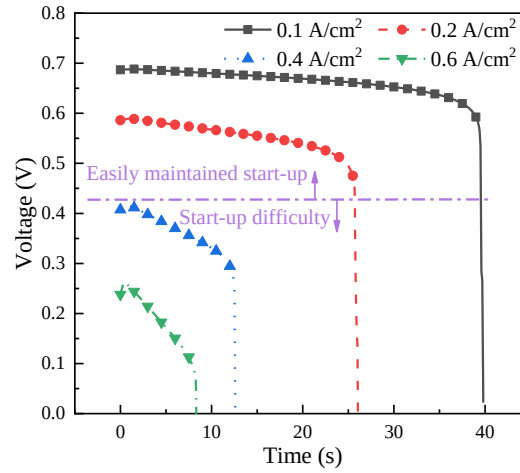


Fig. 3. Polarization curves of different starting current densities.

Fig.4 shows the variation of temperature with time during fuel cell startup at different current densities. The interior of the fuel cell begins to warm up as time increases. The inlet channel temperature hardly changes during startup. The temperature is highest at the cathodic CL where the chemical reaction is the most intensive, and decreases gradually in the direction of flow channel. The temperature of the fuel cell is generally increasing as the starting current density increases. Taking the running time of 5 s as an example, the maximum temperature of the fuel cell is 253.4 K when $I_{\text{start}} = 0.2 \text{ A/cm}^2$, 254.6 K when $I_{\text{start}} = 0.4 \text{ A/cm}^2$, and 255.8 K when $I_{\text{start}} = 0.6 \text{ A/cm}^2$. This is mainly because higher current densities bring more ohmic heating and increase the exothermic heating of the electrochemical reactions. There is almost no change in the fuel cell temperature during the 15 s startup time at $I_{\text{start}} = 0.2 \text{ A/cm}^2$. In comparison, the fuel cell temperature increases by 1.5 K between 5-15 s at $I_{\text{start}} = 0.4 \text{ A/cm}^2$ and 2.6 K at $I_{\text{start}} = 0.6 \text{ A/cm}^2$.

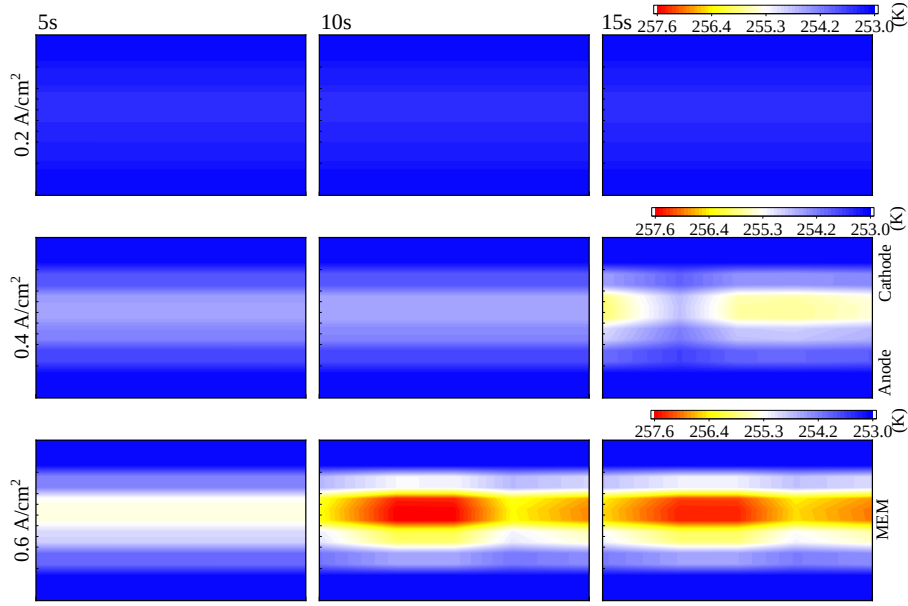


Fig. 4. Temperature distribution at different starting current densities

Although the fuel cell can warm up quickly at high current densities, **Fig. 3** shows that higher current densities cause an earlier startup failure. At this point, the internal heat of the fuel cell is generated entirely by the ohmic resistor and the temperature distribution becomes uneven. As shown in **Fig. 4**, the center of the fuel is invaded by low temperature when running for 15 s at $I_{\text{start}} = 0.4 \text{ A/cm}^2$. The temperature distribution for $I_{\text{start}} = 0.6 \text{ A/cm}^2$ shows that the center of the fuel cell is also invaded by low temperatures at 5 s. However, the fuel cell does not cool down substantially. Instead, there is a small increase in the overall temperature.

Fig. 5a shows the variation of water content in a cathodic CL at different starting current densities. During the cold start, the water content of the cathode CL first increases and then decreases rapidly. The water content peaks at $\sim 4 \text{ s}$ at $I_{\text{start}} = 0.6 \text{ A/cm}^2$, and $\sim 7 \text{ s}$ at $I_{\text{start}} = 0.1 \text{ A/cm}^2$. At the same time, the rate of decrease in cathode water content grows as the current density increases. After the water content reaches a maximum value, the water content within the cathode decreases more rapidly as the current density increases. This is mainly because the temperature is still below freezing, so ice is generated quickly when water is generated in the CL, as shown in **Fig. 5b**. Ice and water are obstacles to the electrochemical reactions in the fuel cell. However, higher current density brings more ice and water. Then the ice phase in the CL occupies all pore space and prevents the electrochemical reaction from proceeding. At this point, it also indicates a cold start failure of the fuel cell.

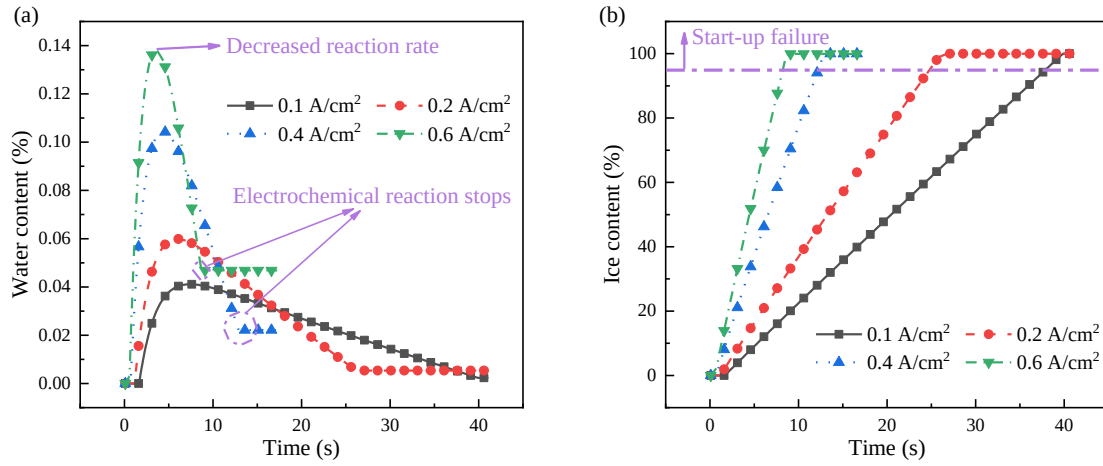


Fig. 5. Distributions of water (a) and ice (b) in the CL.

The maximum water content of the cathode CL increases with starting current density. The highest water content was 0.04% at $I_{\text{start}} = 0.1 \text{ A/cm}^2$ and 0.14% at $I_{\text{start}} = 0.6 \text{ A/cm}^2$. This is mainly because the higher current density provides a higher temperature and a faster chemical reaction rate at the cathode of the fuel cell. At this point, the cathode has a higher saturated membrane water content, while the rate of water production is greater than ice, leading to a higher water content. **Fig. 5b** shows that higher current densities lead to faster blocking of the cathode by ice. The time for 95% cathode ice phase filling at each current density is the same as the time of fuel cell start failure. It can be assumed that the blockage of the cathode CL by ice is the direct cause of fuel cell cold start failure. Therefore, although a high current density provides a higher temperature, the startup failure time at $I_{\text{start}} = 0.6 \text{ A/cm}^2$ is 29 s earlier than $I_{\text{start}} = 0.1 \text{ A/cm}^2$.

3.2 Effect of intake heating method

Since fuel cells with constant current densities cannot start successfully at an environment temperature of -20°C . In this section, intake air heating is considered to assist the PEMFC cold start. The fuel cell polarization curves for intake heating-assisted cold start are shown in **Fig. 6a**. Overall, the cold-start maintains operation at $I_{\text{start}} = 0.2 \text{ A/cm}^2$ for much longer than $I_{\text{start}} = 0.4 \text{ A/cm}^2$. In this case, when the intake gas temperature (T_{inlet}) is 263 K, the fuel cell maintains operation time for 31 s at $I_{\text{start}} = 0.2 \text{ A/cm}^2$, which is 18 s more than $I_{\text{start}} = 0.4 \text{ A/cm}^2$. At $T_{\text{inlet}} = 273 \text{ K}$, the fuel cell maintains operation at $I_{\text{start}} = 0.2 \text{ A/cm}^2$ for 50 s longer than at $I_{\text{start}} = 0.4 \text{ A/cm}^2$. However, there is a different pattern at $T_{\text{inlet}} = 283 \text{ K}$. The fuel cell fails to start and stops operation at about 22 s for $I_{\text{start}} = 0.4 \text{ A/cm}^2$. At this time, the fuel cell voltage rises slowly after 20 s at $I_{\text{start}} = 0.2 \text{ A/cm}^2$. It is preliminarily recognized that the fuel cell cold start was successful.

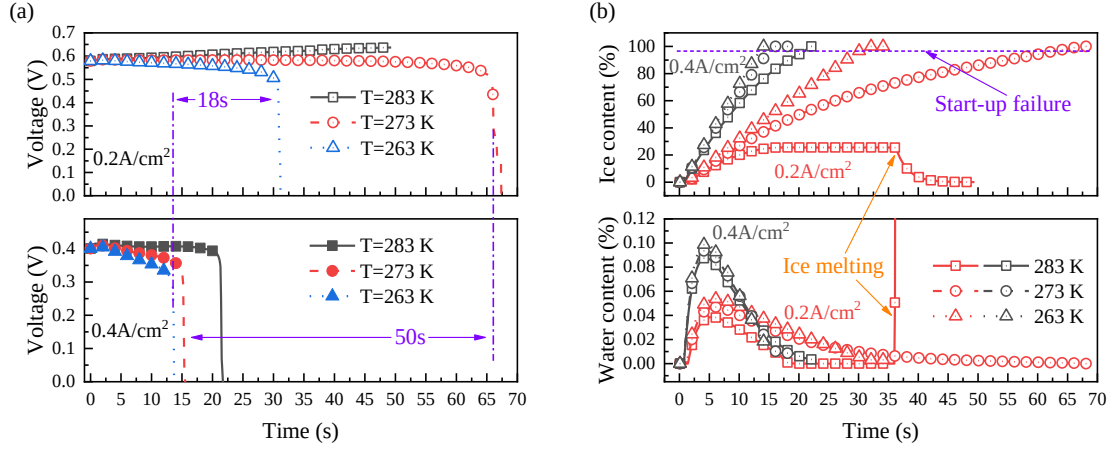


Fig. 6. Polarization curves (a) and contents of liquid water and ice in the cathodic CL (b) of intake heating assisted cold start.

The distributions of ice and temperature changes should also be analyzed. It is obvious that the higher the intake air temperature, the longer the fuel cell maintains operation during the cold start. Moreover, the voltage of the fuel cell drops rapidly at $I_{\text{start}} = 0.4 \text{ A/cm}^2$, while the voltage drops much more slowly or even does not drop at $I_{\text{start}} = 0.2 \text{ A/cm}^2$. This is mainly related to the content of ice and water in the CL of the fuel cell cathode, as shown in **Fig. 6b**. When the ice content in the cathode CL reaches 98% or more, the voltage of the fuel cell will experience a sudden drop and thus the cold start will fail. At $I_{\text{start}} = 0.4 \text{ A/cm}^2$, more water is produced because the chemical reaction is more intense, which will freeze quickly at low temperatures. Therefore, in general, the fuel cell maintains operation for a shorter time at $I_{\text{start}} = 0.4 \text{ A/cm}^2$ than at $I_{\text{start}} = 0.2 \text{ A/cm}^2$. The difference in the rate of ice production at different inlet temperatures is also more pronounced at $I_{\text{start}} = 0.2 \text{ A/cm}^2$. The difference in time to reach 98% ice content in the cathode CL between $T_{\text{inlet}} = 273$ and 265 K is 35 s . However, at $T_{\text{inlet}} = 283 \text{ K}$, the ice in the CL starts to melt at 36 s and rapidly turns into water. This is the reason why the fuel cell can start successfully at $T_{\text{inlet}} = 283$ with $I_{\text{start}} = 0.2 \text{ A/cm}^2$.

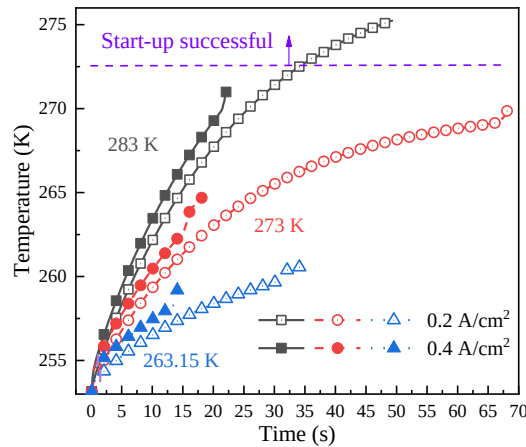


Fig. 7. Fuel cell temperature curves for intake heating assisted cold start.

Similarly, there is a significant difference in the effect of intake gas temperature on the fuel cell cathode, as shown in **Fig. 7**. In the fuel cell cold start process, the temperature reaches above the freezing temperature and can maintain the temperature without dropping, which marks the success of cold start. Obviously, at $T_{\text{inlet}} = 283 \text{ K}$ and $I_{\text{start}} = 0.2 \text{ A/cm}^2$, the temperature of the fuel cell rises to 273 K after 35 s and maintains an increasing trend. At $T_{\text{inlet}} = 283 \text{ K}$, the fuel cell at

$I_{\text{start}} = 0.4 \text{ A/cm}^2$ maintains a faster rate of temperature rise than $I_{\text{start}} = 0.2 \text{ A/cm}^2$. However, the fuel cell with $I_{\text{start}} = 0.4 \text{ A/cm}^2$ stops running at around 22 s and the temperature cannot continue to rise thus the fuel cell startup fails, because the cathode CL reaches over 98% ice content. Overall, the fuel cell temperature rises faster at $I_{\text{start}} = 0.4 \text{ A/cm}^2$ than 0.2 A/cm^2 at all inlet temperatures. A higher temperature of intake gas also results in a faster temperature rise of fuel cell. The rate of temperature rises at $T_{\text{inlet}} = 273 \text{ K}$ is significantly lower than 283 K , and the rate starts to decrease after 35 s. As a result, the fuel cell temperature increases to 270 K at about 66 s, but the startup fails. The cold start performance of the fuel cell is the worst at the intake temperature of 263 K because the heat from the intake-assisted heating is the lowest. In summary, the fuel cell can be cold started successfully at $T_{\text{inlet}} = 283 \text{ K}$ with $I_{\text{start}} = 0.2 \text{ A/cm}^2$, and the startup success time is 35 s.

3.3 Effect of coolant heating method

In practice, separate intake heating requires additional auxiliary equipment, which increases the complexity of the system. Heating the coolant is more easily accomplished by just adding a temperature control to the original equipment. In the present paper, three coolant mass flow rates ($V_{\text{coolant}}^{\text{mass}}$) are selected, concluding $V_{\text{coolant}}^{\text{mass}} = 0.003 \text{ kg/s}$ which is calculated according to the single runner size, $V_{\text{coolant}} = V_{\text{gas}}$, and $V_{\text{coolant}}^{\text{mass}} = V_{\text{gas}}^{\text{mass}}$.

Fig. 8a describes the output voltage of the fuel cell for cold start at $I_{\text{start}} = 0.2 \text{ A/cm}^2$ with coolant heating. When the coolant mass flow rate is 0.003 kg/s and the temperature of coolant (T_{coolant}) is 283 K , the fuel cell voltage remains almost stable during operation. Whereas at 273 K , the fuel cell suddenly drops to 0 V at 62 s , which was 30 s later than at 263 K . When $V_{\text{coolant}}^{\text{mass}} = V_{\text{gas}}^{\text{mass}}$, the output voltage at $T_{\text{coolant}} = 283 \text{ K}$ suddenly drops to 0 V at 76 s , which is 37 s later than $T_{\text{coolant}} = 273 \text{ K}$ and 46 s later than 263 K . However, when $V_{\text{coolant}} = V_{\text{gas}}$, the fuel cell runs 59 s longer at $T_{\text{coolant}} = 273 \text{ K}$ than at 263 K . This is mainly because the faster mass flow rate enhances convective heat transfer at the same coolant temperature. This process increases the heat transfer allowing the cell to maintain better cold start performance. Similarly, at each coolant flow rate, a higher coolant temperature improves the cold start performance of the fuel cell. As an example, when $T_{\text{coolant}} = 273 \text{ K}$, the running time of the fuel cell is 53 s longer at $V_{\text{coolant}} = V_{\text{gas}}$ than at $V_{\text{coolant}}^{\text{mass}} = V_{\text{gas}}^{\text{mass}}$.

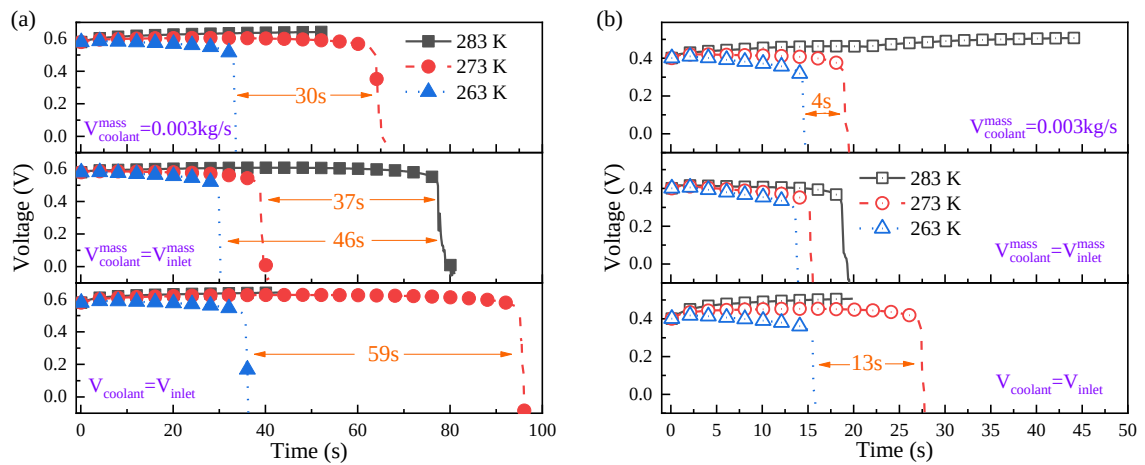


Fig. 8. Output voltage of fuel cell with coolant heating at $I_{\text{start}} = 0.2 \text{ A/cm}^2$ (a) and $I_{\text{start}} = 0.4 \text{ A/cm}^2$ (b).

The output voltage of the fuel cell for cold start at $I_{\text{start}} = 0.4 \text{ A/cm}^2$ exhibits a similar pattern to 0.2 A/cm^2 , as shown

in **Fig. 8b**. The influence of coolant flow and temperature on the cold start is greatly reduced at $I_{\text{start}}=0.4 \text{ A/cm}^2$ compared to 0.2 A/cm^2 . At $V_{\text{coolant}}^{\text{mass}} = 0.003 \text{ kg/s}$, the fuel cell run time at $T_{\text{coolant}}=273 \text{ K}$ is only 4 s longer than at 263 K . However, the effect of coolant temperatures on the cold-start performance is even weaker when $V_{\text{coolant}}^{\text{mass}} = V_{\text{gas}}^{\text{mass}}$. This is mainly because of the faster flow rate of the fuel cell inlet gas at $I_{\text{start}}=0.4 \text{ A/cm}^2$. The low-temperature gas directly contacts the cell porous layer and thus reduces the fuel cell temperature. At the same time, faster electrochemical reactions lead to an increased rate of icing in the CL. These lead to earlier failure of the fuel cell cold start and diminish the effect of the coolant in heating the fuel cell.

Fig. 9a shows the temperature variation curve of the cathode CL in the fuel cell at $I_{\text{start}}=0.2 \text{ A/cm}^2$. Overall, a higher coolant temperature increases the fuel cell cathode CL temperature. Taking $V_{\text{coolant}}^{\text{mass}} = 0.003 \text{ kg/s}$ as an example, the CL of the fuel cell cathode is 274 K when $T_{\text{coolant}} = 283 \text{ K}$, 267 K at $T_{\text{coolant}} = 273 \text{ K}$, and just 260 K at $T_{\text{coolant}} = 263 \text{ K}$. Therefore, the higher the fuel cell temperature increases the total heat loss. In addition, the temperature of the cathode CL increases with the coolant flow rate. The temperature gap of the cell at different coolant temperatures also increases. When $V_{\text{coolant}}^{\text{mass}} = 0.003 \text{ kg/s}$, the temperature of the CL of the fuel cell cathode is 13.5 K higher at $T_{\text{coolant}} = 283 \text{ K}$ than at 263 K . This gap is reduced to 10 K when $V_{\text{coolant}}^{\text{mass}} = V_{\text{gas}}^{\text{mass}}$. While the coolant heats the fuel cell, the cooler fuel and air cause the heat to dissipate from the cell. This also leads to the fact that the flow of high-temperature coolant can affect the cold start performance of the fuel cell.

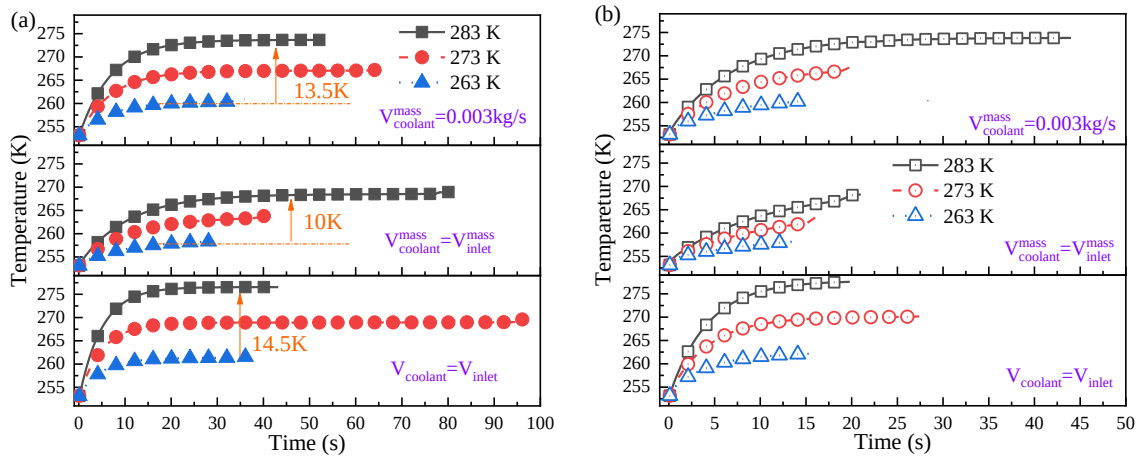


Fig. 9. Temperature of the cathode CL with coolant heating at $I_{\text{start}}=0.2 \text{ A/cm}^2$ (a) and $I_{\text{start}}=0.4 \text{ A/cm}^2$ (b).

However, the temperature of the fuel cell shows different trends at $I_{\text{start}}=0.4 \text{ A/cm}^2$, as shown in **Fig. 9b**. Since the running time of the fuel cell cold start is greatly reduced, the temperature of the cell does not rise to its limit. The temperature of the cathode CL still maintains an increasing trend when the fuel cell stops running at $V_{\text{coolant}}^{\text{mass}} = V_{\text{gas}}^{\text{mass}}$ and $T_{\text{coolant}} = 283$ or 273 K . However, under successful cold start conditions (i.e., $V_{\text{coolant}}^{\text{mass}} = 0.003 \text{ kg/s}$, $T_{\text{coolant}} = 283 \text{ K}$ and $V_{\text{coolant}}^{\text{mass}} = V_{\text{gas}}^{\text{mass}}$, $T_{\text{coolant}} = 283 \text{ K}$), the temperature of the fuel cell is not lower than that at $I_{\text{start}}=0.2 \text{ A/cm}^2$, even though the fuel cell is cooled more intensely at $I_{\text{start}}=0.4 \text{ A/cm}^2$ by the cooler inlet gas. This is because the electrochemical reaction generation and ohmic heats well compensate this heat loss.

As discussed in section 3.2, the success of cold start is determined by the ice content and the temperature of the CL.

Fig. 10 shows variations of water and ice contents in the cathode CL with coolant heating. In general, the ice content rate increases more slowly than the coolant temperature does. A higher coolant flow rate further reduces the ice generation rate.

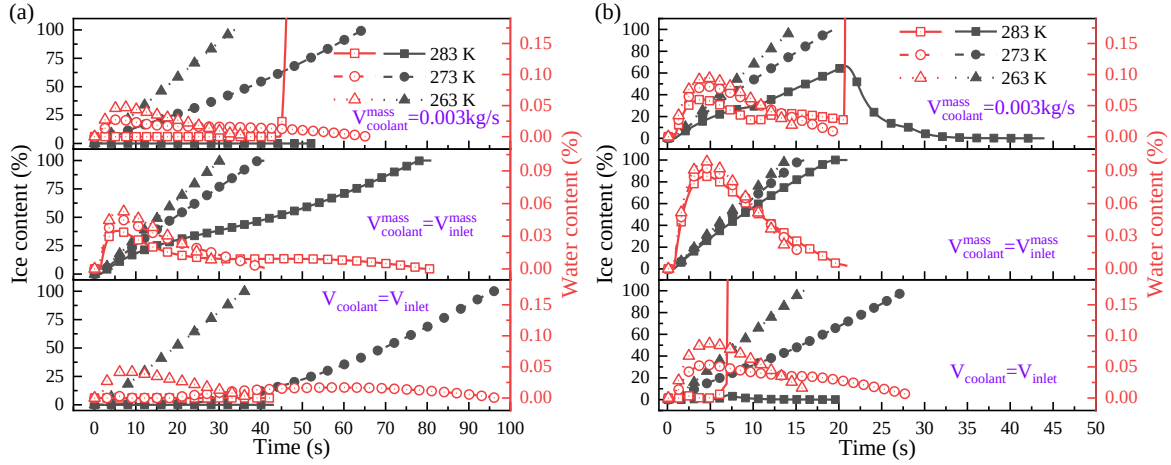


Fig. 10. Water and ice contents in the cathode CL with coolant heating at $I_{\text{start}} = 0.2 \text{ A/cm}^2$ (a) and $I_{\text{start}} = 0.4 \text{ A/cm}^2$ (b).

As shown in **Fig. 10a**, there is no ice production at $V_{\text{coolant}}^{\text{mass}} = 0.003 \text{ kg/s}$, $T_{\text{coolant}} = 283 \text{ K}$ or $V_{\text{coolant}} = V_{\text{gas}}$, $T_{\text{coolant}} = 283 \text{ K}$ when the current density is 0.2 A/cm^2 . This is mainly because the high-temperature coolant causes the fuel cell to warm up quickly, and the slow electrochemical reaction rate generates less water. This also results in the temperature rising above the freezing temperature before ice is generated in the CL. The coolant flow is small at $V_{\text{coolant}} = V_{\text{gas}}$, which has insufficient heat to raise the temperature quickly. So, the ice content of the CL will be over 98%, leading to a cold start failure.

However, the electrochemical reaction produces more water at $I_{\text{start}} = 0.4 \text{ A/cm}^2$ (**Fig. 10b**), resulting in a higher rate of icing than 0.2 A/cm^2 . At $V_{\text{coolant}}^{\text{mass}} = 0.003 \text{ kg/s}$ and $T_{\text{coolant}} = 283 \text{ K}$, the cathode of the fuel cell ices up slowly at first, and the ice content reached 60% at around 20 s. At the same time, because the fuel cell temperature increases to be above the icing temperature, the ice in the CL begins to melt and eventually disappears completely. Overall, the ancillary conditions for a successful fuel cell cold start at 253 K require the coolant temperature to be greater than the freezing temperature of the water. The flow rate of the coolant must be sufficiently high. The fuel cell cold start success time is the earliest (i.e., 8 s) at $I_{\text{start}} = 0.4 \text{ A/cm}^2$, $T_{\text{coolant}} = 283 \text{ K}$ and $V_{\text{coolant}} = V_{\text{gas}}$.

3.4 Performance of current density and heating power matching strategy

Controlling the heating power of the coolant is easier to achieve than controlling the temperature. In this section, an adjustable coolant-assisted heating method matching the step-slope current variation is used to assist fuel cell cold start. The current density, heating power and output voltage are shown in **Fig. 11**. The coolant flow rate is set to 0.003 kg/s . The current density remains constant at 0.2 A/cm^2 until 13 s. At the same time, the coolant heating power is also kept at 25 W . In this process, the voltage of the fuel cell gradually increases until the coolant heating power becomes 0 W at about 15 s. Subsequently, the voltage always maintains a decreasing trend until the coolant heating power becomes 25 W again. At this stage, the voltage change of the fuel cell is still mainly caused by the current density. However, the fuel cell current density increases to a stable value of 0.6 A/cm^2 after 40 s. The coolant heating power becomes the main

influencing factor of the fuel cell performance. The voltage of the fuel cell is gradually increasing in undulating changes as the heating power changes periodically. This phenomenon is mainly caused by the temperature of the cathode CL, which is shown in **Fig. 12**.

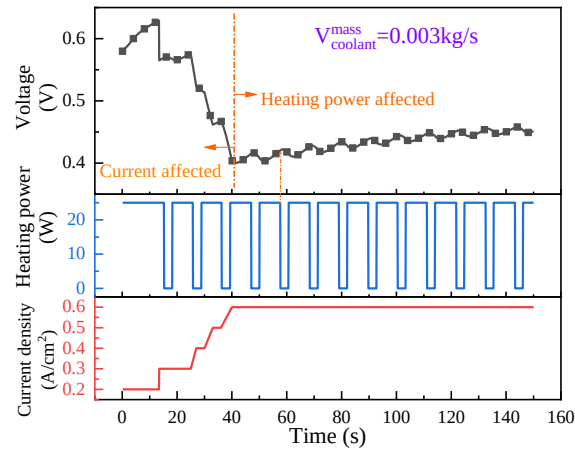


Fig. 11. Variations of current density, voltage and coolant heating power with time.

During fuel cell startup, continuous coolant heating causes a rapid temperature rise. The coolant heating stops when the temperature reaches about 280 K. At this point, the temperatures of the coolant and the fuel cell start to drop, which leads to a decrease in the electrochemical reaction rate. The coolant is reheated when the temperature drops to 277 K. This process is gradually improving the performance of the fuel cell because of the increase in temperature. In the early stages of starting, ice is rapidly generated in the fuel cell as the temperature remains below 273 K. The ice content of the fuel cell cathode reaches 2.2% at around 4 s. Positively, the temperature of the fuel cell rises above 273 K in about 5 s, when the ice starts to melt. The ice content is near 0% after 15 s. The temperature of the fuel cell is also maintained above the freezing point by heating of coolant, when the cold start of the PEMFC is successful.

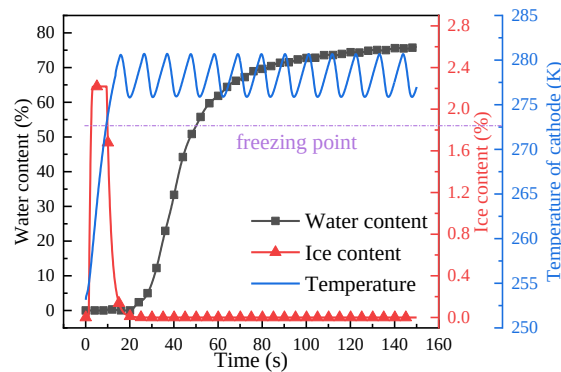


Fig. 12. Variations of temperature, ice and water at the cathode.

Since the fuel cell temperature can be maintained above 273 K, the performance of the fuel cell gradually increases during the operation, as demonstrated in **Fig. 11**. As a result, the water content of the cathode CL increases rapidly. It starts to become slow at around 60 s and gradually approaches 75%. Under this assisted heating method, the voltage and temperature of the fuel cell oscillate and exhibit hysteresis due to the variation of the heating power. Therefore, in the future, an in-depth study of the dynamic response speed of the model is required.

4 Conclusions

This paper investigates the macro- and micro-performance of PEMFC cold-start at low temperatures with assisted heating based on MATLAB Simulink. The evolution patterns of temperature distribution and phase change of water were analyzed. An adjustable coolant-assisted heating method matching the step-slope current variation was proposed to realize an optimal cold-start under low-temperature environments. The main conclusions are as summarized follows:

At a low temperature of 253 K, as PEMFCs cold started, the cathode generated water and solid ice formed in the cathode catalyst layer rapidly, especially under higher starting current density because of much rich water generation. solid ice extended to the cathode gas diffusion layer and the proton exchange membrane, progressively filling the pores. Heating the intake gas emerged as an effective strategy to initiate the cold - start process. Because of the combined effects of coolant heating and internal electrochemical heat generation, the temperature of the electrode plate first raised and conducted heat internally. Subsequently, the temperature of the cathode catalyst layer (CL) surged rapidly, becoming the first to reach 273 K, which was highly conducive to a successful cold-start. In the initial stage, the solid ice at the cathode developed rapidly. The electrochemical reaction was also weakened because the ice occupies the space. Until the temperature of the gas diffusion layer raised above 273 K, the ice in the CL got more heat and melted rapidly.

By implementing the proposed cold - start strategy featuring the adjustable coolant - assisted heating method in tandem with the step - slope current variation, the cathode freezing rate was significantly slowed. The temperature of the cathode catalyst layer raised to 263 K within approximately 5 seconds. At this point, the ice content in the catalyst layer rapidly increased, reaching a maximum value and then remaining constant (2.2%). Around 10 s later, when the temperature of the catalyst layer raised to 274 K, the ice absorbed sufficient heat and begins to melt rapidly, enabling the fuel cell to successfully start within 15 s. While the temperature increased rapidly, the phase change of water was hindered and the permeation of liquid water is sufficiently developed to ensure the humidity of the proton exchange membrane, leading to enhanced fuel cell performance. However, the voltage oscillation needs to be solved by further optimizing the dynamic response speed.

CRedit authorship contribution statement

Shengping Li: Writing - original draft, Writing - review & editing, Conceptualization, Methodology. Huali Zhao: Writing - review & editing, Validation, Investigation. Yuhan Huang: Writing - review & editing, Methodology. Hongyuan Ding and Chunhui Wang: Conceptualization, Supervision. Jiyan Wei: Validation, Investigation. Zhaowen Wang: Writing - review & editing, Formal analysis, Validation, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

The study supported by the project of Combustion and Emission Control Technologies Research for Ammonia-fueled Marine Engines based on the Diesel Cycle and supported by National Key Laboratory of Marine Engine Science and Technology (grant ID: LAB-2023-03).

References

- [1] Sheng C, Fu J, Li D, et al. Energy management strategy based on health state for a PEMFC/Lithium-ion batteries hybrid power system [J]. *Energy Conversion and Management*, 2022, 271.
- [2] Huang Y, Surawski N C, Yam Y-S, et al. Re-evaluating effectiveness of vehicle emission control programmes targeting high-emitters [J]. *Nature Sustainability*, 2020, 3(11): 904-7.
- [3] Huang Y, Lee C K C, Yam Y-S, et al. Rapid detection of high-emitting vehicles by on-road remote sensing technology improves urban air quality [J]. *Science Advances*, 2022, 8: eabl7575.
- [4] Luo Y, Jiao K. Cold start of proton exchange membrane fuel cell [J]. *Progress in Energy and Combustion Science*, 2018, 64: 29-61.
- [5] Hu K, Chu T, Li F, et al. Effect of different control strategies on rapid cold start-up of a 30-cell proton exchange membrane fuel cell stack [J]. *International Journal of Hydrogen Energy*, 2021, 46(62): 31788-97.
- [6] Luo M, Zhang J, Zhang C, et al. Cold start investigation of fuel cell vehicles with coolant preheating strategy [J]. *Applied Thermal Engineering*, 2022, 201.
- [7] Tao J, Wei X, Ming P, et al. Order reduction, simplification and parameters identification for cold start model of PEM fuel cell [J]. *Energy Conversion and Management*, 2022, 274.
- [8] Wang F, Zhang H, Ming P, et al. Experimental study on rapid cold start-up performance of PEMFC system [J]. *International Journal of Hydrogen Energy*, 2023, 48(57): 21898-907.
- [9] Weber A Z, Borup R L, Darling R M, et al. A Critical Review of Modeling Transport Phenomena in Polymer-Electrolyte Fuel Cells [J]. *Journal of The Electrochemical Society*, 2014, 161(12): F1254-F99.
- [10] Xu S, Dong F, Yin B. Mesoscopic process of multiphase reactive flow and heat transfer during direct cold start process in Pt/C particle coated in ionomer of PEMFC [J]. *Chemical Engineering Journal*, 2024, 494.
- [11] Macedo-Valencia J, Sierra J M, Figueroa-Ramírez S J, et al. 3D CFD modeling of a PEM fuel cell stack [J]. *International Journal of Hydrogen Energy*, 2016, 41(48): 23425-33.
- [12] Niu H, Ji C, Wang S, et al. Quantitative analysis on cold start process of a PEMFC stack with intake manifold [J]. *International Journal of Hydrogen Energy*, 2022, 47(4): 2647-61.
- [13] Wei L, Dafalla A M, Jiang F. Effects of reactants/coolant non-uniform inflow on the cold start performance of PEMFC stack [J]. *International Journal of Hydrogen Energy*, 2020, 45(24): 13469-82.
- [14] Pan M, Li D, Pan C, et al. Maximum power tracking-based adaptive cold start strategy for proton exchange membrane fuel cell [J]. *Energy Conversion and Management*, 2022, 273.
- [15] Lei L, He P, He P, et al. A comparative study: The effect of current loading modes on the cold start-up process of PEMFC stack [J]. *Energy Conversion and Management*, 2022, 251.
- [16] Liu J, Chen H, Zhang T. Analysis of cold start characteristics in a PEMFC stack with different current loading modes [J]. *International Journal of Hydrogen Energy*, 2024, 51: 1456-76.
- [17] Gießgen T, Jahnke T. Assisted cold start of a PEMFC with a thermochemical preheater: A numerical study [J]. *Applied Energy*, 2023, 331.
- [18] Tsai S-W, Chen Y-S. A mathematical model to study the energy efficiency of a proton exchange membrane fuel cell with a dead-ended anode [J]. *Applied Energy*, 2017, 188: 151-9.
- [19] Rajbongshi B M, Shaneeth M, Verma A. Investigation on sub-zero start-up of polymer electrolyte membrane fuel cell using un-assisted cold start strategy [J]. *International Journal of Hydrogen Energy*, 2020, 45(58): 34048-57.

- [20] Wang C, Zhan Z, Wan X, et al. Phasic icing phenomena of part single cells during the successful cold start processes of PEMFC stacks [J]. *International Journal of Hydrogen Energy*, 2024, 50: 262-78.
- [21] Chang H, Yang Z, Tu Z. Experimental study on the cold-start performance of a gas heating assisted air-cooled proton exchange membrane fuel cell stack [J]. *Renewable Energy*, 2024, 234.
- [22] Tao X, Sun K, Chen R, et al. Effect of gas diffusion layer parameters on cold start of PEMFCs with metal foam flow field [J]. *Applied Energy*, 2024, 364.
- [23] Yue L, Wang S, Zhu Y, et al. Experimental study on cold start performance of PEMFC based on parallel flow channels [J]. *International Journal of Hydrogen Energy*, 2022, 47(1): 540-50.
- [24] Wang P, Li L. Cold start optimization of the proton-exchange membrane fuel cell by penetrating holes in the cathode micro-diffusion layer [J]. *International Journal of Hydrogen Energy*, 2022, 47(86): 36650-8.
- [25] Hu H, Xu X, Mei N, et al. Numerical study on the influence of waveform channel and related design parameters on the cold start of proton exchange membrane fuel cell [J]. *Solid State Ionics*, 2021, 373.
- [26] García-Salaberri P A, Sánchez-Ramos A. A numerical analysis of the effect of layer-scale and microscopic parameters of membrane electrode assembly in proton exchange fuel cells under two-phase conditions [J]. *Journal of Power Sources*, 2024, 593.
- [27] Jiao K, Li X. Three-dimensional multiphase modeling of cold start processes in polymer electrolyte membrane fuel cells [J]. *Electrochimica Acta*, 2009, 54(27): 6876-91.
- [28] Yang X, Meng X, Sun J, et al. Study on internal dynamic response during cold start of proton exchange membrane fuel cell with parallel and serpentine flow fields [J]. *Journal of Power Sources*, 2023, 561.
- [29] Lin R, Zhong D, Lan S, et al. Experimental validation for enhancement of PEMFC cold start performance: Based on the optimization of micro porous layer [J]. *Applied Energy*, 2021, 300.
- [30] Dafalla A M, Wei L, Liao Z, et al. Influence of cathode channel blockages on the cold start performance of proton exchange membrane fuel cell: A numerical study [J]. *Energy*, 2023, 263.
- [31] Tamilarasan S, Wang C-K, Shih Y-C, et al. Generative adversarial networks for stack voltage degradation and RUL estimation in PEMFCs under static and dynamic loads [J]. *International Journal of Hydrogen Energy*, 2024, 89: 66-83.
- [32] Saidi S, Marrouchi S, Alhasnawi B N, et al. Precise parameter identification of a PEMFC model using a robust enhanced salp swarm algorithm [J]. *International Journal of Hydrogen Energy*, 2024, 71: 937-51.
- [33] Wang Z, Gao Y, Yu J, et al. Data-driven fault diagnosis of PEMFC water management with segmented cell and deep learning technologies [J]. *International Journal of Hydrogen Energy*, 2024, 67: 715-27.
- [34] Zhang H, Wang Y, He S, et al. Real-time prediction models for remaining cold start time in proton exchange membrane fuel cell based on stack temperature [J]. *Case Studies in Thermal Engineering*, 2023, 52.
- [35] Zhang F, Zhang X, Wang B, et al. -30°C cold start optimization of PEMFC based on a data-driven surrogate model and multi-objective optimization algorithm [J]. *Digital Chemical Engineering*, 2024, 10.
- [36] Liu Z, Mao X, Kang Z, et al. Multi-objective optimization of ice distribution uniformity and startup failure time for cold start of PEMFC catalyst layer based on CTnet and PSO-GA [J]. *Fuel*, 2024, 363.
- [37] Yang Z, Jiao K, Wu K, et al. Numerical investigations of assisted heating cold start strategies for proton exchange membrane fuel cell systems [J]. *Energy*, 2021, 222.
- [38] Kim S, Jeong H, Lee H. Cold-start performance investigation of fuel cell electric vehicles with heat pump-assisted thermal management systems [J]. *Energy*, 2021, 232.
- [39] Wang B, Wu K, Yang Z, et al. A quasi-2D transient model of proton exchange membrane fuel cell with anode recirculation [J]. *Energy Conversion and Management*, 2018, 171: 1463-75.
- [40] Springer T E, Zawodzinski T A, Gottesfeld S. Polymer Electrolyte Fuel Cell Model [J]. *Journal of The Electrochemical Society*, 1991, 138: 2334.

- [41] Thomas A. Zawodzinski J, Derouin C, Radzinsk S, et al. Water Uptake by and Transport Through Nafion®117 Membranes [J]. Journal of The Electrochemical Society, 1993, 140: 1041.
- [42] Tajiri K, Tabuchi Y, Kagami F, et al. Effects of operating and design parameters on PEFC cold start [J]. Journal of Power Sources, 2007, 165(1): 279-86.