

Article

Improving Proton Exchange Membrane Fuel Cell Operational Reliability Through Cabin-Based Fuzzy Control in Costal Standalone Observation Systems in Antarctica

Jin Wang ^{1,2} , Yinke Dou ^{1,2,*} , Guangyu Zuo ^{1,2,*}, Bo Fan ¹ and Yuru Xing ¹

¹ Key Laboratory of Cleaner Intelligent Control on Coal & Electricity, Ministry of Education and College of Electrical and Power Engineering, Taiyuan University of Technology, Taiyuan 030024, China; wangjin0048@link.tyut.edu.cn (J.W.)

² Shanxi Energy Internet Research Institute, Taiyuan 030032, China

* Correspondence: douyinke@tyut.edu.cn (Y.D.); zuoguangyu@tyut.edu.cn (G.Z.)

Abstract: Hydrogen energy generation plays a crucial role in enhancing the utilization of clean energy at coastal stations with abundant wind and solar resources in Antarctica. In response to the reliable demand for the application of hydrogen fuel cells in standalone observation systems in Antarctica, in this research, a power supply scheme based on a proton exchange membrane fuel cell (PEMFC) is introduced. Transient models of the PEMFC are developed, and the optimum operational and environmental conditions are determined through experimental investigations conducted at low temperatures. Based on the findings, a PEMFC-based power supply system is designed, encompassing a fuel cell stack, a measurement and control system, and an operation cabin. A temperature-coordinated control system leveraging a BP neural network, fuzzy logic rules, and the fuzzy-based active disturbance rejection control (Fuzzy-ADRC) strategy are proposed to ensure that the temperature of the PEMFC and cabin can reach the optimal state rapidly and that the output voltage is stable. The results indicate that the stack temperature reaches the specified value more rapidly than with PID and ADRC control methods when the current loading and changes in the ambient temperature are considered, and the output voltage oscillation amplitude can be more effectively minimized. This research provides preliminary guidance for a reliable energy supply scheme for PEMFCs, especially in standalone observation systems in coastal locales.

Keywords: Antarctica; standalone observation system; PEMFC; fuzzy logic rules; ADRC



Academic Editors: Wei-Hsin Chen, Aristotle T. Ubando, Chih-Che Chueh, Liwen Jin and Yanjun Sun

Received: 24 December 2024

Revised: 6 January 2025

Accepted: 8 January 2025

Published: 9 January 2025

Citation: Wang, J.; Dou, Y.; Zuo, G.; Fan, B.; Xing, Y. Improving Proton Exchange Membrane Fuel Cell Operational Reliability Through Cabin-Based Fuzzy Control in Costal Standalone Observation Systems in Antarctica. *J. Mar. Sci. Eng.* **2025**, *13*, 112. <https://doi.org/10.3390/jmse13010112>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

The Qinling, Zhongshan, and Great Wall Stations, established by China, are coastal scientific research stations that are situated, respectively, on the western side of the Ross Sea in West Antarctica and on King George Island and the Lassmann Hills in East Antarctica. Among them, Zhongshan Station stands as the largest scientific research station owned by China, while Qinling Station is the one closest to the sea. As is well known, Antarctic research stations provide strong logistical support for team members, which is manifested not only in the accommodations provided but also in the energy and power required for scientific research activities and safe operations. This is especially important in coastal station areas, where the abundant renewable resources facilitate more convenient utilization [1]. As mentioned in previous research, Zhongshan Station, with its abundant wind and solar resources, possesses a combination of complementary characteristics as a coastal station.

It holds significant demonstrative value in studying the energy supply of mixed energy systems and field standalone observation systems (SOSs) within the station area [2]. Wind power generation systems have also been constructed at other coastal stations in Antarctica, such as the German Georgvon Neumayer Station, the Belgian Princess Elisabeth Station, and Scott Base, with these wind farms boasting a maximum power capacity of 54 kW [3].

However, it is necessary to improve the utilization of the clean energy resources available at research stations in Antarctica, especially coastal stations. This is because a power generation system that solely relies on wind and solar resources, which exhibit intermittent and fluctuating outputs, is insufficient to fully meet the demand for clean energy. As an example, a diesel power generation system is required as the primary energy source at Zhongshan Station, as well as at other coastal stations, due to the significant load requirements and the low reliability of wind turbines in these locations [4].

As an emerging energy storage method for power systems, hydrogen energy storage boasts numerous advantages compared to traditional methods. These include being clean and green; having a high energy density, large reserve capacity, and long operating life; and being easy to store and transmit. It can better adapt to the volatility and intermittency of renewable resources, absorbing the excess energy generated by these resources [5]. In Antarctica, during polar nights or when the load demand is high, hydrogen fuel cell (HFC) power generation technology is utilized to convert chemical energy into electricity. For instance, during its 17th and 18th Antarctic expeditions, India studied and deployed a 500 W capacity proton exchange membrane fuel cell (PEMFC) power supply system for an SOS at Maitri Station. Researchers also conducted a series of scientific experiments under optimized conditions, including an ideal reactant temperature, humidification system, air cooling system, and metal hydride hydrogen storage mode. The station successfully completed the design and installation testing of the HFC power supply [6]. Moreover, in 2021, Russia introduced its construction plan for the “Snowflake Research Station” on the Arctic islands, which was designed to be fully diesel-free and powered primarily by hydrogen; its formal implementation began in 2024 [7,8]. During the 40th Antarctic expedition of China, a space physics observatory equipped with a 1 kW HFC power supply system was established at Zhongshan Station, and a clean energy microsystem integrating “wind–solar–hydrogen–storage–load” was set up. After being successfully installed and debugged, it generated its first unit of electricity [9]. A hydrogen energy power generation system with a capacity of 100 kW was also constructed during China’s 41st Antarctic expedition in 2024, which is currently underway at the site [10].

Scholars have conducted extensive research on hydrogen-powered propulsion systems for ships in various coastal port scenarios. Nivolianiti et al. [11] (2024) optimized the energy management strategy for PEMFCs, energy storage systems, and internal combustion engines using a control method based on fuzzy logic rules, resulting in reduced fuel consumption. Truong et al. [12] (2024) optimized the energy management and power allocation of PEMFCs in a hybrid energy storage system on ships, achieving an improved state of charge in the energy storage devices. Jung et al. [13] investigated PEMFC-based energy management strategies based on deep reinforcement learning, achieving a power generation efficiency of 60%, but the operating costs were 0.7% to 9.2% higher than those obtained using dynamic programming-based algorithms. For HFCs in power generation systems at coastal stations in Antarctica, specific meteorological characteristics such as low temperatures and strong winds must be considered, as they can negatively impact the systems, leading to issues such as cold start failures, rapid performance degradation, and reduced load-carrying capacities. Therefore, control strategies for the initial and operating conditions of PEMFCs regarding start-up, operation, and power output are crucial to mitigate these impacts [14].

Some scholars have conducted research on the internal mechanisms and low-temperature control strategies for single-cell and stacked PEMFCs. Min et al. [15] (2022) proposed a cold start method based on current control. Compared with that achieved using other modes, the cold start time at 263 K was shortened by 25.6 s to 41.6 s, and the ice volume fraction was reduced by 29.4% to 31.8%. In addition, in order to avoid performance degradation caused by cold starts, an inertia link was added to the controller, which reduced the current amplitude by 7.98% and the maximum rate of change by 57.44%, making the output electric energy more stable and reliable. Amamou et al. [16,17] (2018, 2020) proposed an adaptive cold start strategy for a vehicle PEMFC based on the maximum power mode. This strategy was based on the optimal operating conditions for the PEMFC's cold start-up process, and the current density was maintained at a high level through the water discharge and self-heating processes of the PEMFC. This served to improve the performance of the PEMFC through membrane hydration and a temperature increase. Zhan et al. [18] (2018) conducted a cold start test on a 2 kW stack using different preheating methods such as air preheating, coolant preheating, and air and end-plate preheating. The results showed that the air preheating speed was slow along the way, while the heating end-plate speed was faster and saved time. Fang et al. [19] (2017) proposed a sliding mode controller with an extended Kalman filter to regulate the temperature of a PEMFC cooling system. The results showed that, without considering the heat generated under various working conditions, the coolant temperature at the outlet of the HFC stack was maintained within the range of 1 K. Ko and Ju et al. [20–22] (2012, 2014, 2015) established a multiphase transient model of a PEMFC during start-up at low temperatures. They also examined the formation and evolution of ice inside the stack, as well as the complex interaction mechanism among heat transfer, mass transfer, and electrochemical reactions. A transient simulation was carried out at 273.15 K to clarify the influence of key factors on cold start operation, including cathode stoichiometry, external thermal boundary conditions, inlet relative humidity (RH), and starting temperature. An effective starting strategy based on a three-dimensional transient cold start model was proposed to increase the current of the PEMFC in the unsaturated internal water stage, thus accelerating the rise in the stack temperature. Lin et al. [23] (2014) studied the current density distribution of a PEMFC during rapid cold starts using printed circuit board technology. The results showed that increasing the initial load and setting the temperature could help to shorten the cold start time and realize the fast preheating of the PEMFC. Zhou et al. [24] (2014) proposed and evaluated a variable heating and load control method for automotive PEMFCs. The results showed that the cold start performance was significantly improved. Tabe et al. [25] (2012) clarified the internal freezing mechanism of a PEMFC through microscopic observation. The results showed that the amount of water produced during cold start-up was related to the initial wetting state of the polymer electrolyte film. Lei et al. [26] (2022) used a one-dimensional transient numerical model to study the effects of different current loading modes on the start-up of a stack at 273 K. The results showed that, among the five loading modes, the current loading mode with a gradual change had advantages such as a fast temperature rise rate, low ohmic impedance, a small ice volume fraction, and a high water production rate, making it the best loading mode. Gißgen et al. [27] (2023) proposed a two-dimensional transient physical model for the coupling of a PEMFC and thermochemical preheater, and the results showed that a lower voltage generated a higher heating rate, which was conducive to cold starts. Li et al. [28] (2019) adopted an external auxiliary heating method to place heating wires on the surface of the membrane electrode of an HFC, aiming to increase the initial temperature of the stack and prevent cold start failures caused by the formation of ice. Mahjoubi et al. [29] (2019) proposed a method to simultaneously control the stack temperature and the air metering ratio so that the load

current, the air metering ratio, and the stack temperature were in the optimal working area. Li et al. [30] (2015) proposed an ADRC method for the precise temperature regulation of a PEMFC. The results showed that the proposed control system allowed the PEMFC to operate successfully at 343 K in the presence of two different disturbances.

The PEMFC is a nonlinear time-varying system with complex internal parameters and multiphase changes. Under different operating conditions such as loading and unloading at low temperatures, the temperature and output voltage of the stack will change accordingly, which will reduce the output performance of the PEMFC [31]. To exploit the advantages of PEMFCs for SOSs in Antarctica and meet the demands for HFCs to have a substantial power share in renewable energy generation systems, it is crucial to investigate the output characteristics of PEMFCs under sub-zero temperatures and varying humidity conditions and to provide effective operation and output control strategies. Existing research on coastal HFC energy supplies primarily focuses on hybrid energy optimization management, fuel consumption reduction, and operational cost lowering in marine propulsion systems. In terms of control strategies, studies have predominantly focused on PEMFCs for vehicular applications, with limited research on the sensitivity of PEMFC performance to environmental conditions and their applications in stationary power generation systems.

In this work, we propose a reliable energy supply solution for PEMFCs in Antarctic SOSs, with full consideration of the impact of the coexisting low-temperature and low-humidity meteorological conditions at Antarctic coastal stations on PEMFC performance. We focus on the need for a thermal balance between the production and dissipation of heat in PEMFCs for temperature control to ensure stable operation, and we highlight the unique aspects of PEMFC operation and power output in stationary power generation systems in Antarctica, providing a foundation for comprehensive research on PEMFCs deployed at coastal stations with various meteorological conditions. Section 2 introduces the cold start model and operating mechanism of a PEMFC at sub-zero temperatures, analyzing its low-temperature operational characteristics. Section 3 presents the working mechanism of an operation cabin for PEMFCs, along with an analysis of the effectiveness of temperature coordination control. Section 4 discusses in detail the control strategies used to ensure the stable and reliable power output of PEMFCs under varying loads, considering the energy demands of SOSs. The results of case studies are presented in Sections 3 and 4. Finally, Section 5 concludes this paper.

2. Transient Model of PEMFCs

2.1. Operation Mechanism of PEMFCs

2.1.1. Working Principles

The PEMFC described in this work primarily consists of nine components: two bipolar plates (BPs), two channels (CHs), two gas diffusion layers (GDLs), two catalyst layers (CLs), and a proton exchange membrane (PEM). During the formation of the stack, two end plates are added for clamping and assembly. As shown in Figure 1, the BPs, CHs, GDLs and CLs are found in both the anode and cathode. For example, the BP of the anode is represented as ABP, the CL of the cathode is represented as CCL, and other components are similarly represented.

In a PEMFC, energy is supplied to the load and other electrical units by converting chemical energy into electrical energy. This complex process of energy conversion involves nonlinear control conservation equations, such as those for electrode dynamics, electrochemistry, thermodynamics, and fluid mechanics. Its performance in outputting electrical energy to the external environment depends on the membrane's water absorption state, the membrane's current density, and the voltage loss caused by the activation overpotential, ohmic overpotential, and concentration overpotential induced by the gas excess

ratio. The performance of the cells can be characterized using a polarization curve. The polarization curve shown in Figure 2 was obtained from an operating experiment on an air-cooled PEMFC.

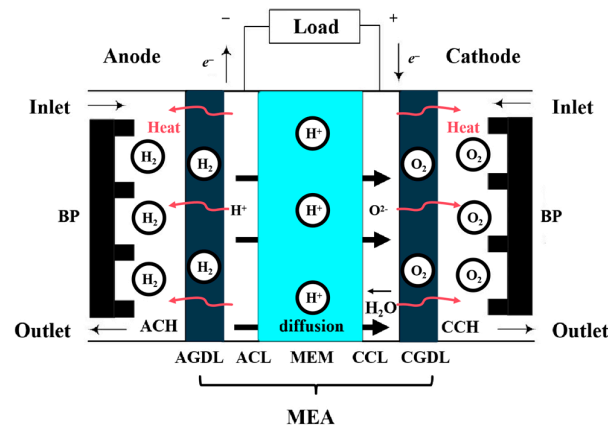


Figure 1. Schematic diagram of a PEMFC.

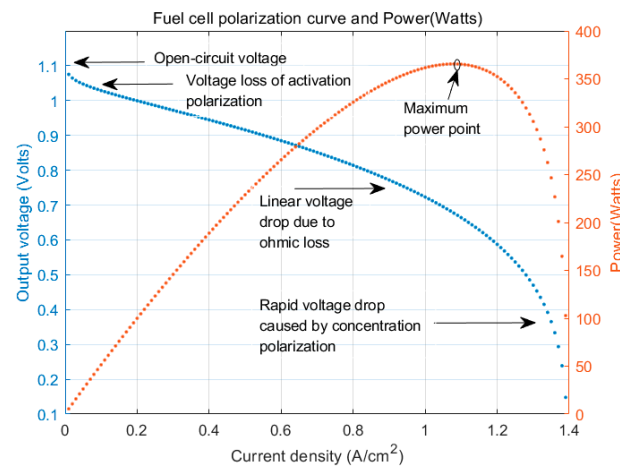


Figure 2. Polarization curve of a PEMFC.

The voltage output equation is expressed in Equation (1) [11]:

$$V_{\text{out}} = E_{\text{nerst}} - V_{\text{act}} - V_{\text{ohm}} - V_{\text{con}} \quad (1)$$

where V_{out} , E_{nerst} , V_{act} , V_{ohm} , and V_{con} represent the output voltage, open-circuit voltage, activation overpotential, ohm overpotential, and concentration overpotential of the FC, respectively.

From Figure 2, it can be seen that with an increase in the current density, the HFC voltage gradually decreases, and the output state of high current density represents the carrying capacity of the HFC [32]. At a low current density, the lower voltage loss is caused by activation polarization. As the current density increases, the voltage decreases linearly, mainly due to the ohm overpotential. At a high current density, the output voltage of the cells drops rapidly due to the decrease in the gas concentration near the membrane electrode and in the gas channels and diffusion layers. In the process of increasing the current density, the output power will reach the highest point when the concentration overpotential is small, which is the maximum output power point of the HFC limit.

2.1.2. Internal Mechanism Model

In order to analyze the external output performance, which is characterized by the internal mechanism of the HFC, the low-temperature mechanism of a single-cell model is established using the control conservation equation.

(1) Mass conservation

The mass conservation transport in the HFC is expressed according to the continuity equation:

$$\frac{\partial(\varepsilon(1 - S_{lq} - S_{ice})\rho_g)}{\partial t} + \nabla \cdot (\rho_g u_g) = S_m \quad (2)$$

where ε is the porosity of the GDL and CL, the size of which is the ratio of the volume of the voids in the microporous layer to the volume of the microporous layer. S_{lq} and S_{ice} are the volume fractions of liquid water and ice accumulation. ρ_g is the density of mixed gas (kg/m^3); u_g is the velocity vector of gas entering the stack. S_m is the HFC mass component source term.

(2) Momentum conservation

The momentum conservation equation describes the velocity of the gas flow inside the HFC:

$$\frac{1}{\varepsilon} \left[\frac{\partial(\rho_g u_g)}{\partial t} + \frac{1}{\varepsilon} \nabla \cdot (\rho_g u_g u_g) \right] = -\nabla p + \nabla \cdot \tau + S_u \quad (3)$$

where p is the pressure of the gas flow (pa), τ is the viscosity, and S_u is the momentum source term.

(3) Energy conservation

The energy conservation equation is used to characterize the changes in the internal temperature of the HFC:

$$\frac{\partial(\varepsilon \rho_g C_{gp} T_g)}{\partial t} + \frac{\partial(\varepsilon \rho_{cell} C_{cell} T_{cell})}{\partial t} + \nabla \cdot (\rho C_p u T) = \nabla \cdot (\kappa^{eff} \nabla T) + S_T \quad (4)$$

where C_{gp} , C_{cell} , and C_p are the gases, the HFC, and the convective specific heat capacities ($\text{J}/\text{kg}/\text{K}$), respectively; T_g , T_{cell} , and T are the temperatures (K) of the gases, the HFC, and the convective heat transfer, respectively; u is the velocity vector of gas convective heat transfer; ρ is the density of each item (kg/m^3); κ^{eff} is the heat conduction coefficient ($\text{W}/\text{m}/\text{K}$), where the empirical value is taken; and S_T is the energy source term.

(4) Species conservation

$$\frac{\partial(\varepsilon C_i)}{\partial t} + \nabla \cdot (u C_i) = \nabla \cdot (D_i^{eff} \nabla C_i) + S_i \quad (5)$$

$$D_i^{eff} = \varepsilon^n \left(\frac{1}{D_i^g} + \frac{1}{D_i^k} \right)^{-1} \quad (6)$$

$$D_i^g = \frac{1 - x_j}{\sum_{i,i \neq j}^n \frac{x_i}{D_{ij}}} \quad (7)$$

$$D_i^k = \frac{2}{3} \left(\frac{8Ru \cdot T}{\pi i \cdot M_i} \right)^{0.5} \quad (8)$$

where C_i is the concentration of different components (mol/m^3); D_i^{eff} is the effective diffusion coefficient of different components and is the sum of the porosity diffusion coefficient D_g and the curvature diffusion coefficient D_k . x_i and x_j are the exchange coefficients of the components, and there is mixed diffusion between them. D_{ij} is the mixed diffusivity

between the components, Ru is the Knudsen number, and M_i is the molar mass of the different components (g/mol).

(5) Voltage equation

Based on the voltage equation represented by Equation (1), each corresponding expression is obtained.

$$E_{\text{erst}} = U_0 + \frac{RT_{\text{mea}}}{2F} \cdot \ln \frac{p_{\text{H}_2} p_{\text{O}_2}^{0.5}}{p_{\text{H}_2\text{O}}} \quad (9)$$

$$U_0 = 1.23 - 9 \times 10^{-4} (T_{\text{mea}} - 298.15) \quad (10)$$

$$V_{\text{act}} = -\frac{RT_{\text{mea}}}{\alpha F} \cdot \ln \left(\frac{I c_{\text{ref}}}{(1-s)^{0.5} j_A c^{\delta_{\text{cl}}}} \right) \quad (11)$$

$$V_{\text{ohm}} = I(R^{\text{elec}} + R^{\text{proton}}) \quad (12)$$

$$V_{\text{con}} = \frac{RT_{\text{mea}}}{\alpha F} \cdot \ln \left(1 - \frac{I}{j_D} \right) \quad (13)$$

$$j_D = \frac{4Fc}{\delta_{\text{GDL}}/D_{\text{GDL}} + 0.5 \cdot \delta_{\text{CL}}/D_{\text{CL}}} \quad (14)$$

where T_{mea} is the membrane's electrode temperature (K); T_0 is the standard temperature, namely, 298.15 K; R is the universal gas constant, 8.134 (J/kg/K); p_{H_2} , p_{O_2} , and $p_{\text{H}_2\text{O}}$ are the hydrogen pressure, oxygen pressure, and water vapor pressure (Pa), respectively; U_0 is the equilibrium potential of the electrochemical reaction (V); α is the transfer coefficient; c_{ref} is the reference molar concentration (mol/m³); s is the ice volume fraction; j_A is the exchange current density (A/m³); c is the molar concentration of the reactant (mol/m³); I is the FC current (A); R^{elec} and R^{proton} are the impedance of electrons passing through the collector plate and the equivalent impedance of protons passing through the PEM (Ω), respectively; δ_{GDL} and δ_{CL} are the thicknesses of the gas diffusion layer and the catalytic layer (mm); j_D is the limit current density (A/cm²); and D_{GDL} and D_{CL} are the effective mass diffusivities of the gas diffusion layer and the catalytic layer, respectively (m²/s).

Based on the above, a model of the PEMFC's cold start mechanism is constructed on the ANSYS platform (2022 R1 version), and we compare the simulation results of the model with those in the literature [33]. After reviewing the experimental conditions described in the literature, the relevant parameters of the model are set accordingly (see Table 1 for specific parameters), and the initial temperatures are -3 °C and -20 °C. The fuel gas stoichiometric ratio is 3/3.5. The initial ice volume fraction is set to 0. Figures 3 and 4 show comparisons of the HFC's voltage and current density, respectively, during the cold start process under different initial voltages and temperatures, as obtained via the model and from the literature [33].

Table 1. Parameter settings of the PEMFC mechanism model.

Item	Description	Value
$\delta_{\text{mem}}, \delta_{\text{CL}}, \delta_{\text{GDL}}$	Thickness of mem, CL, GDL (mm)	0.05, 0.01, 0.2
$\varepsilon_{\text{CL}}, \varepsilon_{\text{GDL}}$	Porosity of CL, GDL	0.53, 0.6
$C_{\text{p},i}$	Specific heat capacity of liquid water, ice, gas, and mem (J/kg/K)	4182, 2050, 2014, 833
$\sigma_{\text{CL}}, \sigma_{\text{GDL}}$	Effective electronic conductivity of CL, GDL (S/m)	300, 300
$\kappa_{\text{CL}}, \kappa_{\text{GDL}}, \kappa_{\text{mem}}$	Thermal conductivity of CL, GDL, mem (W/m/K)	1.2, 1.5, 0.95
j_A	Exchange current density (A/m ³)	$10^{-6.912}$
α	Transfer coefficient	0.5
$x_{\text{H}_2}, x_{\text{N}_2}, x_{\text{O}_2}$	Exchange coefficients of components	7.07, 17.9, 16.6
R	Gas constant (J/kg/K)	8.314
F	Faraday constant (C/mol)	96,485

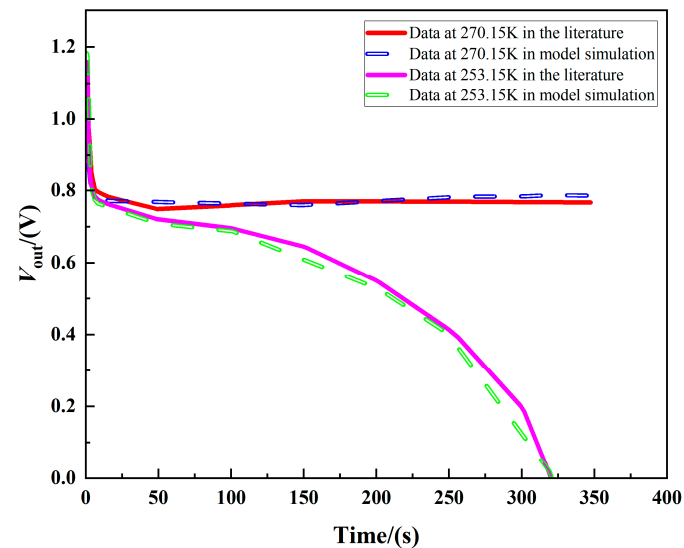


Figure 3. Comparison between model predictions and experimental data on PEMFC voltage (270.15 K and 253.15 K).

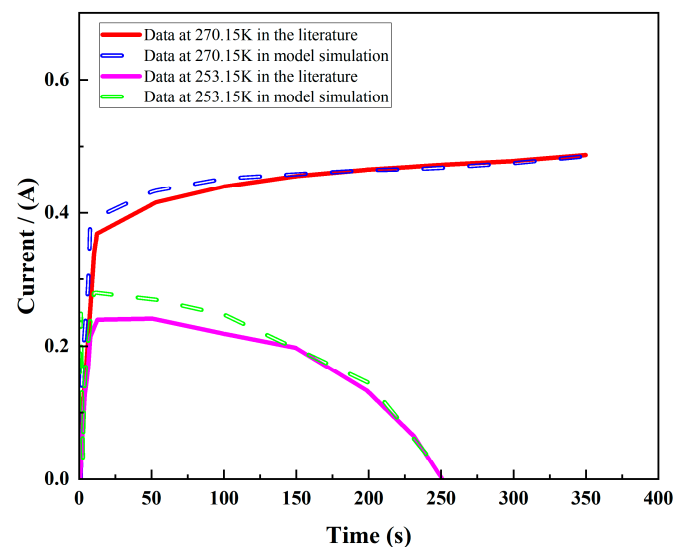


Figure 4. Comparison between model predictions and experimental data on PEMFC current (270.15 K and 253.15 K).

As shown in Figures 3 and 4, the voltage obtained via the model established in this work is in good agreement with the results presented in the literature. In the initial stage of PEMFC start-up, the current density calculated with the model is slightly higher than the experimental value provided in the literature. The obtained variation in the voltage and current density is basically the same as that reported in the literature, and the error between them remains within 3%.

The reason for the difference in the current density is that, at low temperatures, the water produced by the PEMFC has three forms. In the initial stage of the stack, the electrochemical reaction releases less heat, resulting in a very weak vaporization phase transition in the water. In this section, the effect of water vapor is considered in the model, as this effect is ignored in the literature. In the initial stage of the stack, the water phase transition will absorb and remove part of the heat, resulting in a slight decrease in the internal temperature of the stack. This slows down the electrochemical reaction rate and reduces the efficiency, and the current value exhibits the opposite trend to the efficiency

change; thus, the current density value will be slightly higher than the results described in the literature.

2.2. Low-Temperature PEMFC Performance

Based on the simulation and analysis of the single-cell mechanism model in the previous section, the performance of the stack in a low-temperature environment similar to that of Antarctica must be evaluated. In this section, the heat exchange between the air and the stack is changed by adjusting the fan speed of the air-cooled PEMFC, so as to determine the best working temperature and enable cooperative temperature control. Since the air-cooled PEMFC has an open cathode and self-humidifying structure, the hydration state of the PEM is also affected by the fan speed, so different ambient temperatures and humidity levels will affect the hydration state of the PEM. Specifically, the output power of the stack changes, so the operation of an air-cooled PEMFC requires the optimal operating temperature. This optimal operating temperature will change when the environmental conditions change.

2.2.1. Low-Temperature Experiment

(1) Experimental conditions

The experiment is carried out with a DC electronic load with a maximum power of 1.5 kW. There are three modes: constant voltage, constant current, and constant power. In order to explore the influence of different environmental conditions on the operation of an air-cooled PEMFC, the experiment is performed in a laboratory that can provide a constant-temperature and -humidity environment. The temperature range is $-50\sim 90\text{ }^{\circ}\text{C}$, and the humidity range is 10~90%.

Based on Equations (1)–(14), an air-cooled HFC with rated power of 30 W is selected for the low-temperature experimental test and analysis. Its stack contains 21 cells, which can support a load power consumption of 0~2.3 A under a normal-temperature environment. The PEMFC and the monitoring module used in the experiment are shown in Figure 5, including the stack, controller, cooling fans, sensors, hydrogen loop, and data communication module. The working conditions set in the experiment are shown in Table 2.

Table 2. Parameter settings in the low-temperature experiment.

Item	Value
Rated power (W)	30
Rated voltage (V)	13.2
Rated current (A)	0.3, 0.6, 0.9, 1.2, 1.5, 1.7, 2.3
Voltage range (V)	11~22
Hydrogen purity (%)	99.999
Hydrogen pressure (kPa)	40~50
Air pressure (bar)	1.01325
Weight (kg)	0.73
Dimensions (cm)	13.3*7.1*6.7
Operating current (A)	0.3, 0.6, 0.9, 1.2, 1.5, 1.7, 2.3
Ambient humidity (%)	40, 60, 80
Ambient temperature (K)	268.15, 273.15, 278.15, 283.15, 288.15, 293.15

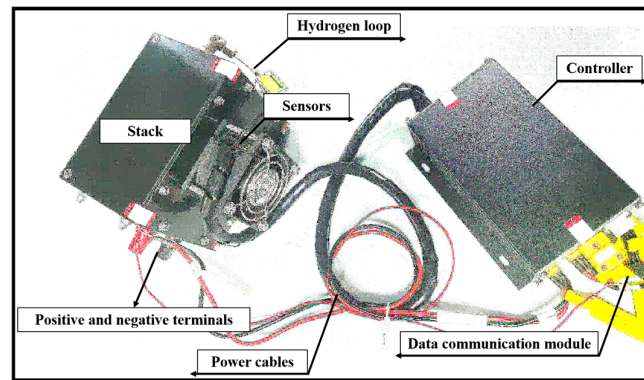


Figure 5. PEMFC monitoring module.

(2) Experimental methods

In order to explore the relationships between different environmental factors, the load current, and the optimal operating temperature of the HFC, as well as to eliminate the interference of irrelevant factors and ensure the experimental results, the following rules are formulated:

- (1) The HFC is fully activated through gradual loading before the experiment.
- (2) After the completion of “(1)”, the anode channel of the stack is fully purged, and the fan is synchronously opened to ensure that the water vapor volatilizes rapidly [34,35].
- (3) The temperature and humidity of the experimental environment are kept relatively constant. The load current is set to a constant value, and the stack output voltage and stack temperature are recorded.
- (4) The voltage consistency among individual cells within the stack is high.
- (5) The frequency of the stack parameter acquisition is once per second, with real-time data transmission.
- (6) High-resolution analog-to-digital conversion devices and double-precision sensors are used.
- (7) The flow rate and pressure of hydrogen are kept constant.

2.2.2. Experimental Analysis

Through the analysis of the experimental data, it is found that the output performance of the stack is the best under a load current of 1.7 A, an ambient temperature of 293.15 K, and an RH of 60%. The relationship between the output voltage and stack temperature under these conditions is shown in Figure 6.

As can be seen in Figure 6, there is a peak voltage point in the working process of the air-cooled PEMFC, i.e., the best working temperature point (corresponding to the temperature at 9 min after the experiment begins). With an increase in the stack’s operating temperature, the stack voltage presents a trend of first rising and then decreasing, and the highest output voltage appears near a certain temperature value, which corresponds to the highest output power at 1.7 A. Therefore, the optimum operating temperature points under different environmental conditions can be obtained by controlling the temperature of the PEMFC stack. The relationship between the optimal working temperature of the stack and the load current under the conditions of an ambient temperature of 268.15 K–293.15 K and an RH of 60% is shown in Figure 7.

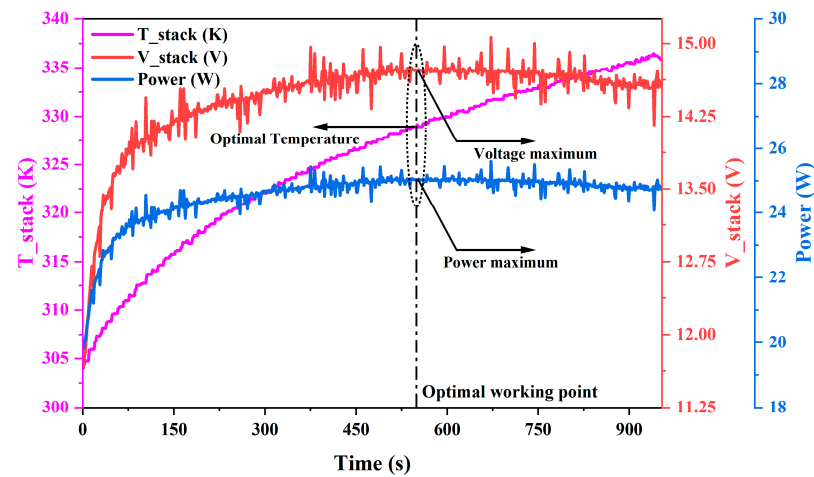


Figure 6. Voltage, power, and stack temperature curves (load current: 1.7 A, ambient temperature: 293.15 K, RH: 60%).

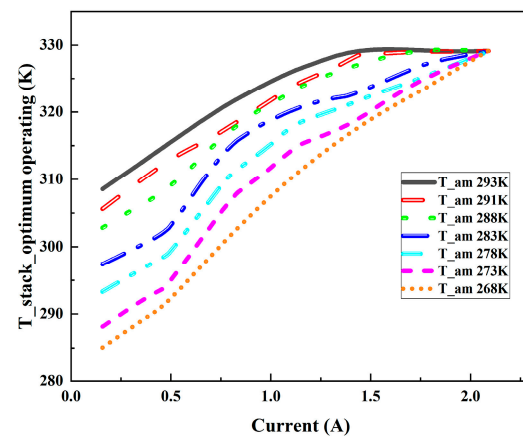


Figure 7. Optimum working temperature and load current curve of the stack (ambient temperature: 268.15 K to 293.15 K; RH: 60%).

As can be seen in Figure 7, when the RH is constant, the higher the ambient temperature, the higher the optimal working temperature of the stack. An analysis of the experimental data shows that, when the current of the stack is less than 0.6 A and the ambient temperature is less than 283 K, the HFC fails to reach the optimal operating temperature point. This is due to the low ambient temperature. When the stack's working current is low, the electronic fan is unable to meet the anode's minimum oxygen requirement. This will also cause excessive convective heat dissipation in the stack, and it is unable to reach the best working state.

When the current is greater than 0.6 A, the hydration state of the PEM can be balanced earlier; as the heat production of the stack increases, the catalyst activity can reach its peak earlier, and the stack can reach the best working temperature point. When the ambient temperature is greater than 283 K, an increase in the ambient temperature reduces the convective heat dissipation of the fuel cell stack, allowing it to reach its optimal operating temperature point. Regarding the protection of the fuel cell stack, an exploration of the relationship between the pressure drop and the temperature rise in the stack at higher temperatures is not conducted here. However, experiments have shown that when the stack temperature exceeds 328.15 K, the stack voltage fluctuates significantly; after multiple experiments, the output voltage of the fuel cell drops drastically. Therefore, in this study, the maximum temperature of the stack is set at 328.15 K.

In the process of HFC power generation, the chemical reaction rate increases with the increase in temperature, and the output voltage increases correspondingly. For PEMs, insufficient water content will reduce the mass transfer rate, and excessive water content will cause flooding [36]. Therefore, it can be determined from the output characteristics that the hydration state of the PEM and the activity of the catalyst are optimal when the output voltage of the stack is the maximum. As the temperature continues to rise, although the reaction rate and catalyst activity further increase, the water evaporation rate of the PEM also increase, resulting in water loss at high temperatures, as well as a voltage drop and fluctuations. Therefore, it is necessary to prevent the PEMFC's temperature from exceeding the limit value. Moreover, in order to ensure that the HFC operates optimally, the temperature of the stack should be controlled so that it is near the optimal working temperature point according to the environmental conditions and the load current.

In an air-cooled self-humidifying PEMFC, part of the water in the PEM comes from the water generated by the reaction, and the other part comes from the air; thus, the ambient humidity will affect the output characteristics of the PEMFC. Figure 8 shows the relationship between the output voltage, stack temperature, and ambient humidity at an ambient temperature of 291 K and a current of 1.5 A. In this case, the environmental humidity is set to various low values that are characteristic of China's Antarctic coastal research stations.

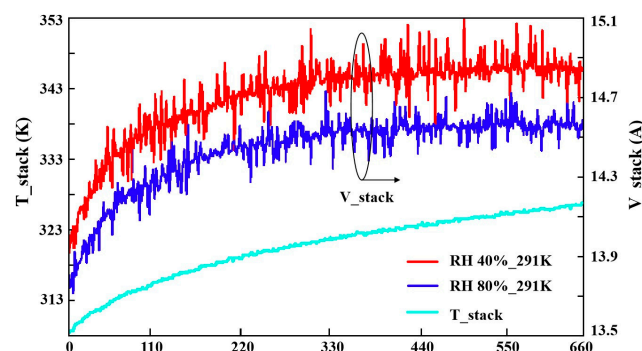


Figure 8. Curves of voltage, stack temperature, and ambient humidity (ambient temperature: 291 K, load current: 1.5 A).

It can be seen in Figure 8 that at a certain ambient temperature and working current, the output voltage of the stack differs with different levels of ambient humidity. Regarding the HFC used in this experiment, the peak voltage difference in the stack can reach 0.5 V under different levels of ambient humidity, and this difference will decrease with an increase in current.

The relationship between the optimal working temperature of the stack and the load current under the conditions of ambient temperature (283 K, 291 K) and ambient humidity (40%, 80%) is shown in Figure 9.

When the ambient temperature is 291 K and the stack current is less than 1.5 A, the optimal working temperature of the stack increases as the ambient humidity rises. As the current increases, however, this effect is reversed: a higher ambient humidity leads to a lower optimum operating temperature, although this temperature gradually converges toward a common value. The impact of the humidity on the stack is primarily manifested in its output voltage. This is because as the current increases, the rate of water generation within the stack also increases, which is subsequently mitigated by the ambient humidity. Conversely, at an ambient temperature of 283 K, higher ambient humidity results in a lower optimal operating temperature. Table 3 presents the optimum operating temperature data obtained under various experimental conditions.

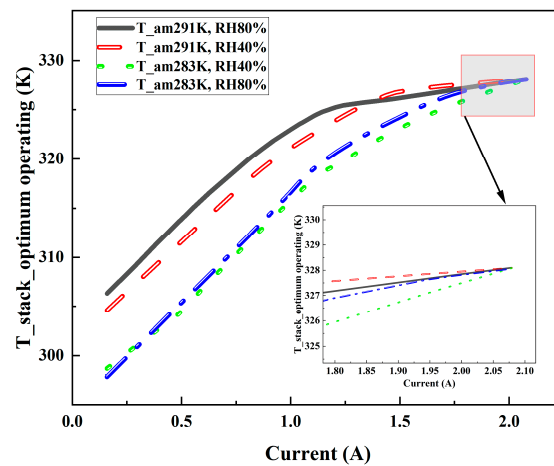


Figure 9. Optimum working temperature and load current curve of the stack (ambient temperature: 283 K, 291 K; ambient humidity: 40%, 80%).

Table 3. Optimum operating data under different experimental conditions.

Ambient temperature (K)	268.15	278.15	278.15	288.15	291.15	291.15	291.15	293.15
Ambient humidity (%)	60	40	60	60	40	60	80	60
Load current (A)	Optimum operating temperature for the stack (K)							
	Load voltage (V)							
	Time at optimum operating temperature (min)							
0.3	285.15	297.75	297.15	302.55	304.65	305.15	306.35	308.05
	16.69	17.28	17.11	17.41	17.31	17.29	17.16	17.24
	35	28.2	27.5	25	21.4	21	20.7	20.5
0.6	291.55	304.15	302.45	308.15	311.25	311.95	313.45	314.55
	16.14	16.28	16.35	16.69	16.47	16.48	16.35	16.46
	27.5	18.3	18	17.1	16.8	16.5	16.2	16
0.9	301.45	311.55	314.35	316.65	317.75	317.25	319.85	320.55
	15.75	15.76	15.82	16.07	15.89	15.83	15.71	15.85
	19.8	17.8	17.3	16.5	16.3	16.2	16.2	16
1.2	310.15	318.35	319.65	322.45	322.85	323.15	324.55	325.25
	15.34	15.23	15.29	15.46	15.28	15.32	15.04	15.19
	15.2	14.7	14.1	13.2	13.2	13	13	12.8
1.5	317.15	322.45	322.15	326.25	326.45	327.55	326.05	328.15
	14.99	14.81	14.88	15.02	14.86	14.85	14.57	14.74
	14.5	13.1	12.6	12.1	12	11.8	11.5	11.4
1.7	322.65	325.75	326.15	328.15	327.65	328.15	327.05	328.15
	14.71	14.49	14.55	14.68	14.52	14.5	14.29	14.39
	12.1	11	10.5	9.8	9.5	9.4	9.4	9.2
2.3	328.15	328.15	328.15	328.15	328.15	328.15	328.15	328.15
	13.72	13.32	13.38	13.64	13.52	13.5	13.23	13.38
	10	9.2	8.5	6.6	5.7	5.1	4.8	4.3

Based on the optimal working temperature and corresponding output voltage data, at a constant humidity level, the output voltage of the stack is greater at an ambient temperature of 288.15 K. The stack requires 17.6 min to reach its optimal working temperature at 273.15 K and 0.9 A. At 278.15 K and 0.6 A, the stack requires 18.3 min to reach its maximum temperature. Meanwhile, at 288.15 K and 0.3 A, the stack requires 25 min to achieve its optimal operating temperature. Therefore, to enhance the power generation efficiency and response speed, it is advisable to moderately increase the ambient temperature in

low-current conditions to improve the responsiveness, while it is recommended to decrease it in high-current conditions to enhance the output voltage.

3. Collaborative Temperature Control

3.1. Control System Design

For the application of a PEMFC for an SOS in Antarctica, it is necessary to address the challenges of low-temperature storage and cold start issues. It is imperative to provide an optimal operational environment for air-cooled PEMFCs to ensure their normal functioning, enhance their power generation efficiency, and improve the stability of their power supply.

According to the meteorological data obtained from Qinling Station during China's 40th Antarctic scientific expedition and previous work at the Zhongshan and Great Wall Stations [2,3], the lowest temperature of the three stations can reach 223.15 K throughout the year. Figure 10 shows the meteorological data curve.

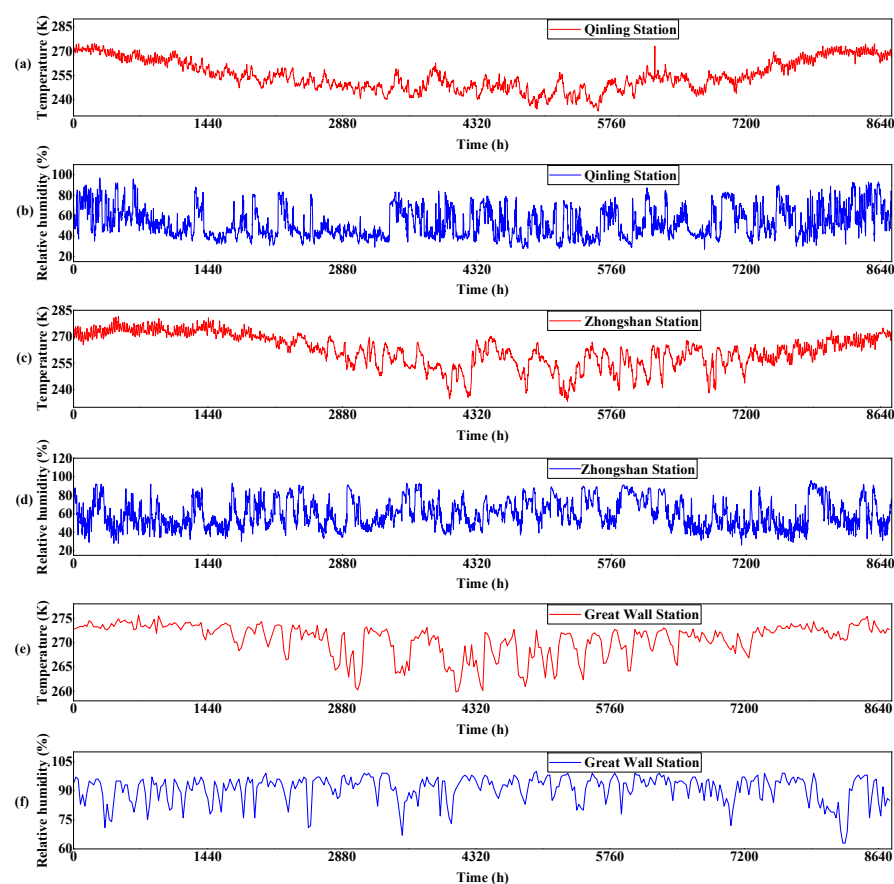


Figure 10. Meteorological curves in Antarctica: (a) temperature at Qinling Station; (b) RH at Qinling Station; (c) temperature at Zhongshan Station; (d) RH at Zhongshan Station; (e) temperature at Great Wall Station; (f) RH at Great Wall Station.

The data presented in Figure 10, derived from ERA reanalysis data, represent the temperature and humidity for the three coastal stations throughout the year from January to December. As shown in Figure 10, Qinling Station experiences significant temperature fluctuations throughout the year, with the lowest average temperature of 255 K. During the polar night, the temperature can drop as low as 233 K, occurring specifically on 22 August. The annual average temperature at Zhongshan Station and Changcheng Station are 261.9 K and 270.6 K, respectively. Qinling Station also has the lowest annual average relative humidity at 53.22%, which is lower than the 59.6% and 91% values recorded at Zhongshan and Great Wall Stations. The lowest and highest relative humidity values at Qinling

3.2. Temperature Control Model

3.2.1. Thermodynamic Model

In addition to the governing equation and voltage models established in Section 2.1.2, the temperature models of the PEMFC and cabin are given. The temperature of the air-cooled PEMFC is mainly affected by electrochemical heat production, output power, heat radiation, and air cooling dissipation. Electrochemical heat generation Q_{generate} (J) mainly includes the reversible heat Q_{rev} (J) generated in the membrane electrode, the irreversible heat Q_{irrev} (J) caused by the polarization phenomenon, and the latent heat Q_{sg} (J), which are expressed in the following way:

$$Q_{\text{generate}} = Q_{\text{rev}} + Q_{\text{irrev}} + Q_{\text{sg}} \quad (15)$$

For an electrode with a 15 cm^2 reaction area A (cm^2), the reversible heat of an HFC operating at a certain temperature and current density can be calculated as follows:

$$Q_{\text{rev}} = (-T_{\text{mea}}\Delta S)\frac{iA}{2F} = (-T_{\text{mea}}\frac{\partial U_0}{\partial T})iA \quad (16)$$

where ΔS is the entropy change within the whole reaction (J/mol/K), i is the current density (A/cm^2), F is Faraday's constant (C/mol), and U_0 is the equilibrium potential (V) of the reaction, which is consistent with the U_0 in the Nernst voltage equation—see Equation (10).

The irreversible heat of the HFC is mainly affected by the electrochemical reaction. During the low-temperature start-up process, the condensation of water will also release heat, and heat will be absorbed in the melting stage, which can be calculated as follows:

$$Q_{\text{irrev}} = (U_0 - V)I \quad (17)$$

$$Q_{\text{sg}} = h_{\text{sg}}n_{\text{ice}}^{\text{H}_2\text{O}} \quad (18)$$

where h_{sg} is the latent heat of the phase change (J/kg) during water condensation. $n_{\text{ice}}^{\text{H}_2\text{O}}$ is the rate of water condensation (mol/s).

The heat inside the stack is calculated using the following:

$$C_{\text{stack}}m_{\text{stack}}\Delta T_1 = Q_{\text{generate}} - Q_{\text{out}} - Q_{\text{air1}} \quad (19)$$

$$C_{\text{stack}}m_{\text{stack}}\frac{dT_1}{dt} = P_{\text{generate}} - P_{\text{out}} - P_{\text{air1}} \quad (20)$$

where C_{stack} is the specific heat capacity of the stack (J/kg/K), m_{stack} is the stack mass (kg), and dT_1 is the temperature change per unit time in the stack. P_{generate} , P_{out} , and P_{air1} (W) are the thermal generation power, output electric energy power, and heat dissipation power of the stack, respectively; these are obtained from the time differentiation of the corresponding thermal energy Q (J) of each item in Equation (19).

3.2.2. Control Method

The neural network model uses the backpropagation (BP), which is a supervised learning algorithm used to train multi-layer feedforward neural networks. After establishing the mathematical model of the PEMFC stack and cabin, a neural network model is used to fit the relationship between the optimal operating temperature of the air-cooled PEMFC and the ambient temperature, humidity, and load current based on the results of the experiments in Section 2, as well as to obtain the optimal temperatures of the desired working environment. Fuzzification and defuzzification based on the fuzzy logic rules for the difference between the optimal operating temperature obtained through the neural network and the actual temperature are performed, which, as inputs of an incremental PID

control algorithm for the deviation between the stack operating temperature and the target temperature, can be controlled rapidly and stably. All models are run in Matlab/Simulink (2019 version), and the model simulation diagram is shown in Figure 12.

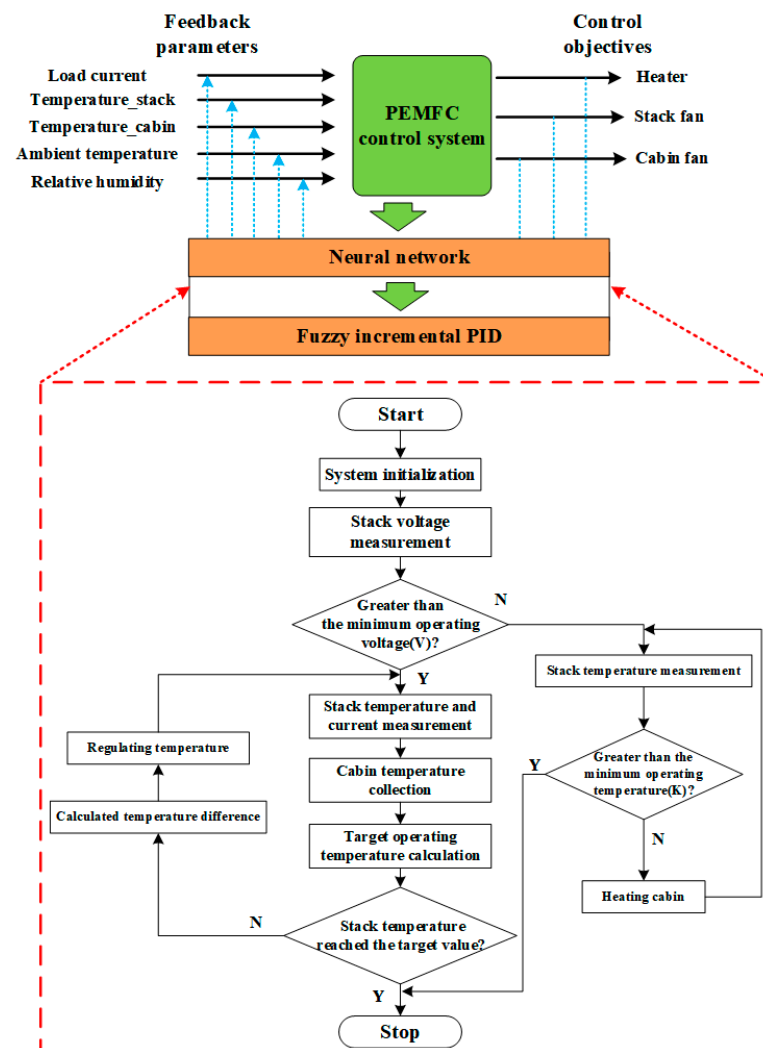


Figure 12. Simulation of algorithms for the cooperative control of temperature.

As shown in Figure 12, the load current, stack temperature, cabin temperature, ambient temperature, and humidity are taken as inputs for the control system. Through coordinated control, the power and opening of the heaters, stack, and cooling fans in the cabin are adjusted. First, real-time monitoring of the key parameters of each component is initiated, with the data being fed back continuously. Second, the target parameters for each control objective are initialized, with the specific values detailed in Table 4.

Table 4. Model validation test conditions.

Initial Stack Temperature (K)	Initial Ambient Temperature (K)	Load Current (A)
273	268	0.9 A
		1.7
		0.5

The difference e_{stack} , e_{cabin} and change rate ec_{stack} , ec_{cabin} obtained by the neural network between the optimal operation temperature and actual temperature are taken as the input of the fuzzy incremental PID controller, and the output is the control parameters

Δp , Δi , and Δd of the stack temperature. Herein, e_{stack} and e_{cabin} are the temperature difference of the stack and cabin, respectively, and their fuzzy domains are $[-24, 24]$ and $[-18, 18]$. The fuzzy domains of ec_{stack} and ec_{cabin} are $[-4, 4]$ and $[-3, 3]$, respectively. The fuzzy domain of control parameters Δp , Δi , and Δd are all $[-2, 2]$. The fuzzy language of the input variables of the fuzzy controller is {NB,NM,NS,ZO,PS,PM,PB}. Thus, the fuzzy control rules for Δp , Δi , and Δd of the stack fan and the cabin heater are presented in Table 5.

Table 5. Fuzzy control rules of control parameters (Δp , Δi , Δd) for the stack fan and cabin.

$\Delta p, \Delta i, \Delta d$ of the stack fan							
e_{stack}	ec_{stack}						
	NB	NM	NS	ZO	PS	PM	PB
NB	PB/NB/PS	PB/NB/NS	PM/NM/NB	PM/NM/NB	PS/NS/MB	ZO/ZO/NM	ZO/ZO/PS
NM	PB/NB/PS	NB/NB/NS	PM/NM/NB	PS/NS/NM	PS/NS/NM	ZO/ZO/NS	NS/PS/ZO
NS	PM/NB/ZO	NM/NS/NM	PM/NS/NM	PM/NS/NM	ZO/ZO/NS	NS/PS/NS	NS/PM/ZO
ZO	PM/NM/ZO	PM/NM/NS	PS/NS/NS	ZO/ZO/NS	NS/PS/NS	NS/PM/NS	NM/PM/ZO
PS	PS/NM/ZO	PS/NS/ZO	ZO/ZO,ZO	PS/PS/ZO	PS/PS/ZO	NM/PM/ZO	NM/PB/ZO
PM	PS/ZO/PB	ZO/ZO/PM	NS/PS/PM	NM/PS/PM	NM/PM/PS	NM/PB/PS	NB/PB/PB
PB	ZO/ZO/PB	ZO/ZO/PM	NM/PS/PM	NM/PM/PS	PS/PM/PS	PM/PB/PS	PB/NM/PB

$\Delta p, \Delta i, \Delta d$ of the cabin							
e_{cabin}	ec_{cabin}						
	NB	NM	NS	ZO	PS	PM	PB
NB	PB/NB/PS	PB/NB/NS	PM/NM/NB	PM/NM/NB	PS/NS/NB	ZO/ZO/NM	ZO/ZO/PS
NM	PB/NB/PS	PB/NB/NS	PM/NM/NB	PS/NS/NM	PS/NS/NM	ZO/ZO/NS	NS/ZO/ZO
NS	PM/NB/ZO	PM/NM/NS	PM/NS/NM	PM/NS/NM	ZO/ZO/NS	NS/PS/NS	NS/PS/ZO
ZO	PM/NM/ZO	PM/NM/NS	PS/NS/NS	ZO/ZO/NS	NS/PS/NS	NS/PM/NS	NM/PM/ZO
PS	PS/NM/ZO	PS/NS/ZO	ZO/ZO/ZO	NS/PS/ZO	NS/PS/ZO	NM/PM/ZO	NM/PB/ZO
PM	PS/ZO/PB	ZO/ZO/NS	NS/PS/PSM	NM/PS/PS	NM/PM/PS	NM/PB/PS	NB/PB/PB
PB	ZO/ZO/PB	ZO/ZO/PM	NM/PS/PM	NM/PM/PM	PS/PM/PS	NB/PB/PS	NB/PB/PB

By comparing the real-time feedback on the stack output voltage, stack temperature, and cabin temperature with their respective target thresholds and evaluating the differences, adjustments are made to the stack and cabin fans, progressively approaching the target values. Lastly, when the control targets reach their preset values, the system remains in a dynamic control process to ensure that the PEMFC operates optimally at all times.

3.3. Model Verification

The initial and change conditions for the PEMFC are shown in Table 4. The fan voltage of the stack is set to the lowest value that can meet the operation requirements. The load current is 0.9 A to 1.7 A, with a step change of 0.5 A. A comparison of the PEMFC's dynamic temperature and output voltage is shown in Figure 13.

As can be seen in Figure 13, when the temperature is stabilized ($t = 719$ s, $t = 1480$ s), the difference between the simulation (sim_T) and experimental (lab_T) results are 1.1 K and 3 K, respectively. The larger the current, the larger the difference between the two. The reason for this is that in the simulation model, the PEM is 100% humidified by default. However, in the experiment, the PEMFC cannot achieve complete humidification, i.e., the RH is not 100%. The dynamic voltage of the PEMFC according to the simulation and experimental results is also consistent. When $t > 1470$ s, the experimental voltage (lab_V) is slightly higher than the simulation voltage (sim_V). This is because the output

voltage of the PEMFC is higher after the operation at a high current, the water content of the PEM increases, and the stack temperature is higher. Then, the stability values of the experiment under the step change in the current are slightly higher than the simulation values. Under the condition that the RH is less than 100%, at the initial current loading, the ohm overpotential brought by the low humidity in the stack is larger than that under 100% humidity, so the experiment value is low. With the continuous loading and step change in the current, the water generated in the stack continuously accumulates, and the overpotential decreases. Thus, the output voltage of the stack in the experiment is gradually greater than the simulated value, even when the experimental result shown in Figure 13 is that the higher temperature value promotes the evaporation of vapor. Moreover, the objective constraints of the seamless implementation of the control method in the hardware control module, such as data transmission and command delivery delay, are also the key reasons for the difference between the experimental and simulation results. Therefore, it can be considered that the PEMFC temperature model is accurate within the allowable error range.

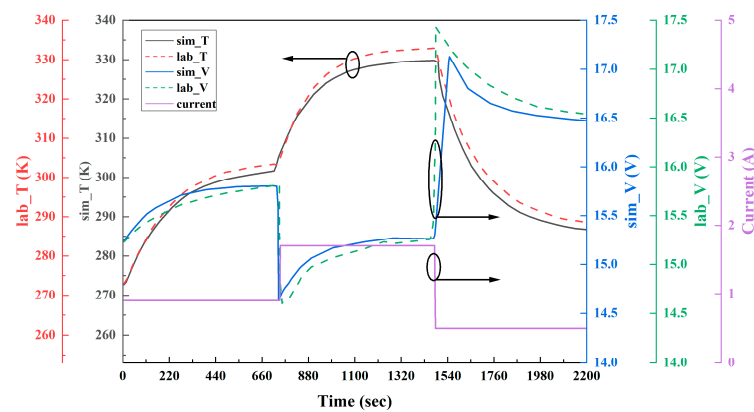


Figure 13. Dynamic temperature and voltage curves (comparison between simulation and experimental results).

According to the above results, this model can accurately reflect the dynamic change processes within the designed temperature control system. The effect of the incremental PID algorithm based on the BP neural network and fuzzy logic rules is compared with that of the PID control method. The initial parameters are presented in Table 6.

Table 6. Control method comparison test conditions.

Initial Stack Temperature (K)	Initial Ambient Temperature (K)	Load Current (A)	Target Temperature (K)
273	268	1 A	390
		2	285
		0.5	300

As can be seen in Figure 14, when the load current is 1 A and the set temperature is 290 K, the steady-state time of the PID control based on fuzzy logic rules (Fuzzy-PID) is 337 s, and the steady-state time of the PID control method is 462 s. Both indicate that there is no overshoot, and the Fuzzy-PID control method has a faster response speed. When the set temperature is lowered to 285 K in this state, Fuzzy-PID control also responds faster. When the load current is 2 A and the set temperature is 300 K, the overshoot with PID control is 1.3 K, and the overshoot with Fuzzy-PID control is 0.3 K; thus, the overshoot in the latter case is smaller.

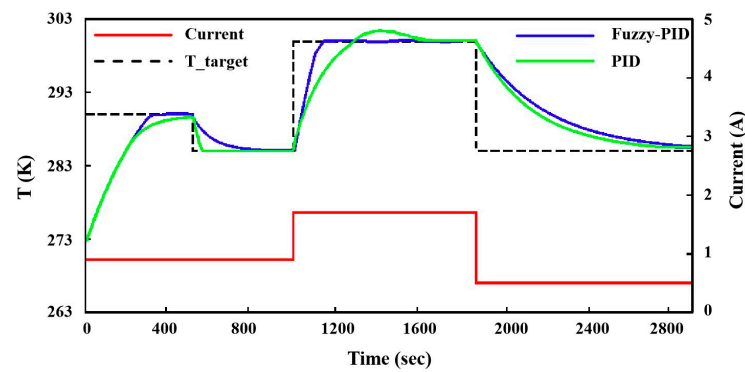


Figure 14. Dynamic temperature curve (comparison of Fuzzy-PID and PID control results).

When the load current is 0.5 A and the set temperature is 285 K, the steady-state error in Fuzzy-PID control is large. On the whole, Fuzzy-PID control has advantages in terms of the response speed and overshoot control, so Fuzzy-PID control has a superior control effect on the air-cooled PEMFC.

In order to better verify the model, a low-temperature simulation and experimental test with an ambient temperature of 253 K are carried out. Figures 15 and 16 show the curves of the simulation and experimental results for the control system, respectively.

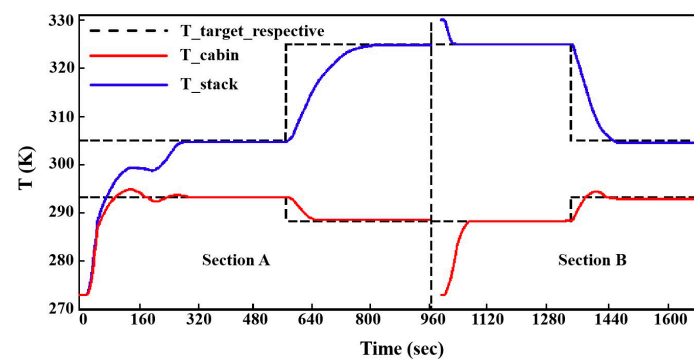


Figure 15. System control temperature change curve.

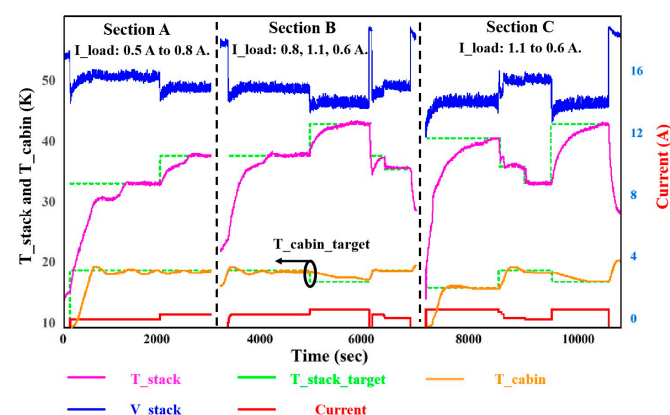


Figure 16. Curve of the experimental results in a low-temperature environment.

As shown in Figure 15, the PEMFC is set to 0 A, the initial temperature of the cabin is 273 K, and the current varies from 0.5 A to 2 A. Due to the existence of a heating device in the cabin, the PEMFC will exhibit a faster temperature rise at low temperatures under the condition of low-current operation, and the temperature response of the PEMFC will increase rapidly. At 96 s, the cabin's temperature is overshoot by 1.4 K due to the combined action of the PEMFC and heater. At 635 s, the load current increases, and the target

temperatures of the PEMFC and cabin change. At this stage, the heat output of the PEMFC increases, but the temperature of the cabin is required to decrease, and the controller can still control the PEMFC and the cabin to reach the target temperature and maintain stability. In area B, the initial temperature of the PEMFC is set at 330 K, the initial temperature of the cabin is 273 K, and the current varies from 2 A to 0.5 A. At this stage, the cooling process of the PEMFC and the heating process of the cabin are simulated. The overshoot of the cabin temperature is 1.1 K, and the error is 0.33 K.

As can be seen in Figure 16, the collaborative control of the temperatures of the stack and the cabin enables the stack to reach the optimal working temperature faster and maintains the stability of the stack temperature and output voltage. In region A, the time required for the load current of the 0.5 A stack to reach a steady state is 310 s, and the time required for the working chamber to reach the set temperature is 190 s. Compared with the case with no temperature control system in Section 2.2.2, the temperature of the PEMFC rises rapidly. Target temperature 1 in region B and target temperature 2 in region C exhibit the same load current, but the ambient humidity is different. The control system adjusts the optimal working temperature of the stack. At the same time, when the load current changes, the system can also adjust the target temperature of the cabin.

4. Control of Output Voltage

A PEMFC is a complex, strongly coupled, nonlinear device that exhibits hysteresis and polarization loss regarding the input reaction gas, resulting in a delayed output voltage response when it is running with a load and pulling a load. Long-term operation will accelerate the performance attenuation of the stack itself and the decline in the load impact resistance. Therefore, according to the above discussion regarding the low-temperature performance, the design and optimization based on ADRC should be considered in the application of PEMFC power generation systems for SOSs in Antarctica. This is necessary due to the inability of the voltage to immediately reach a stable state when it changes with the step current, as described in Section 3.3.

4.1. Output Voltage and Fuzzy-ADRC Method

Equations (21)–(24) represent the ADRC equations, including the tracking differentiator (TD), nonlinear discrete function (*fal*), extended state observer (ESO), and nonlinear state error feedback control law (NLSEF) [30].

$$\begin{cases} e = v_0 - v_1 \\ v_1 = -h \cdot fal(e, \alpha, \delta) \end{cases} \quad (21)$$

$$fal(e, \alpha, \delta) = \begin{cases} |e|^\alpha \text{sgn}(e), & |e| > \delta \\ \frac{e}{\delta^{1-\alpha}}, & |e| < \delta \end{cases} \quad (22)$$

$$\begin{cases} e_1 = V_1 - y \\ V_1 = V_2 - \beta_1 fal(e, \alpha, \delta) + bu \\ V_2 = -\beta_2 fal(e, \alpha, \delta) \end{cases} \quad (23)$$

$$\begin{cases} e = V_0 - V_1 \\ u_0 = \beta \cdot fal(e, \alpha, \delta) \\ u = u_0 - V_2/b \end{cases} \quad (24)$$

where v_0 is the output voltage setting value; v_1 is the input signal after arranging the transition process; h is the discrete control period of the controller; *fal* is the nonlinear discrete function; e is the input and output voltage signal error (V), which is the difference

between the output voltage set value V_0 and the output voltage observed value V_1 ; α is the tracking factor; δ is the filter factor; sgn is a step function; V_1 and V_2 are the FC output voltage state variables (V) of the ESO; and β_1 and β_2 are the error adjustment gains of the ESO. b is the compensation factor; u is the controlled quantity (hydrogen flow); and β is the feedback control law used to adjust the gain.

ADRC based on fuzzy logic rules (Fuzzy-ADRC), removing TD due to the lack of differential signal, can be used to achieve closed-loop control through negative-error feedback, track the system's output values, estimate and compensate for internal and external disturbances in real time, and realize self-adaptation to load disturbances. A sudden change in the load current of the PEMFC is used as the disturbance signal to optimize the output voltage, and fuzzy logic rules are used to optimize the parameters so as to realize the closed-loop control of the input gas flow by controlling the proportional valve. The relationship between the gas flow and output voltage is described according to the law of conservation of energy and the gas state equation, as shown in the following:

$$\frac{V_{\text{an}}}{RT} \cdot \frac{dP_{\text{H}_2}}{dt} = m_{\text{H}_2} - K_{\text{an}}P_{\text{H}_2} + K_{\text{an}}P_{\text{H}_2,E} - \frac{0.5NI}{F} \quad (25)$$

where V_{an} is the total volume of the anode flow field (m^3); R is the gas constant (J/K/mol); P_{H_2} and $P_{\text{H}_2,E}$ are the inlet hydrogen pressure and outlet discharge pressure of the PEMFC anode, respectively; and K_{an} is the anode flow coefficient.

A fuzzy controller consists of a fuzzy domain, fuzzy logic rules, and a membership function. As shown in Figure 17, for ADRC, e and de/dt are taken as the inputs of the fuzzy controller, and the b and β increases are taken as the outputs of the fuzzy controller. According to the inputs and outputs of the fuzzy controller, we can determine e , de/dt , b , and β and establish a fuzzy comprehensive domain; they are, respectively, $[6, 6]$, $[6, 6]$, $[1, 1]$, and $[0.5, 0.5]$. Seven fuzzy subsets are implemented on the discourse domain, which are negative large (NB), negative medium (NM), negative small (NS), zero (ZO), positive small (PS), median (PM), and supersize (PB). The fuzzy control rules are used to set the initial values of b and β as 50 and 0.1, respectively, and to determine the ratio of the b and β increments, $\Delta b/\Delta\beta$, as shown in Table 7.

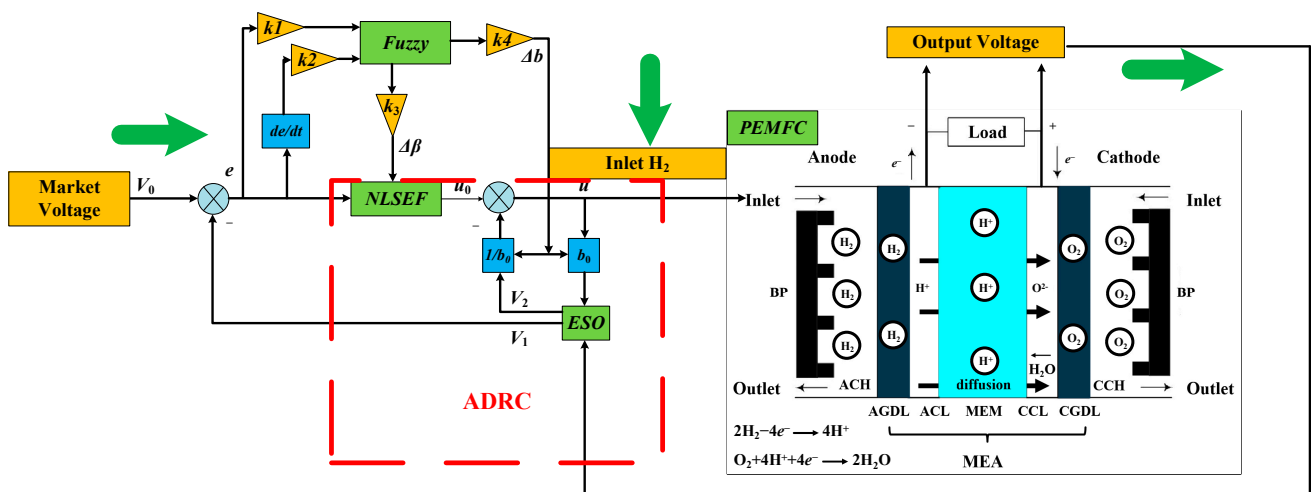


Figure 17. Structure of Fuzzy-ADRC.

Table 7. Fuzzy control rules as the ratio of b to β increases ($\Delta b/\Delta \beta$).

e	de/dt						
	NB	NM	NS	ZO	PS	PM	PB
NB	NB/PB	NB/PB	NM/PB	NM/PM	NS/PS	ZO/ZO	ZO/ZO
NM	NB/PB	NB/PB	NM/PM	NM/PS	NS/PS	ZO/ZO	ZO/NS
NS	NM/PM	NM/PM	NS/PM	NS/PS	ZO/ZO	ZO/NS	PS/NS
ZO	NM/PM	NS/PM	NS/PS	ZO/ZO	PS/NS	PS/NM	PM/NB
PS	NS/PS	NS/PS	ZO/ZO	PS/NS	PM/NM	PM/NM	PM/NM
PM	ZO/PS	ZO/ZO	PS/NS	PM/NM	PM/NM	PB/NM	PB/NB
PB	ZO/ZO	PS/ZO	PM/NM	PM/NM	PB/NM	PB/NB	PB/NB

The membership function and the optimized b and β are determined from the gain using Equations (26) and (27):

$$f = \frac{\sum_{i=1}^q T^*(i)m_c(i)}{\sum_{i=1}^q m_c(i)} \quad (26)$$

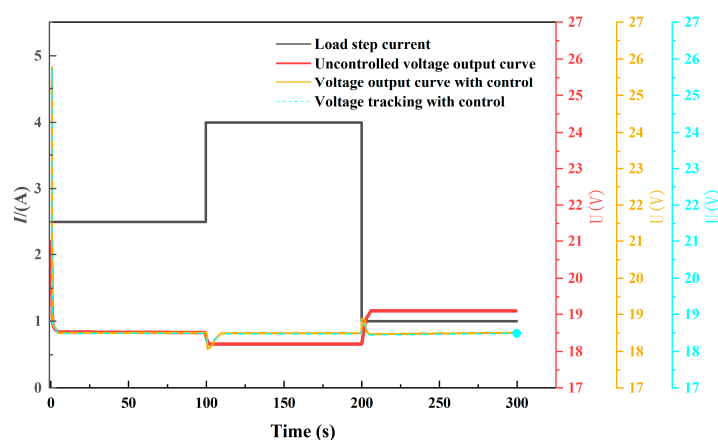
$$\begin{cases} b_0 = b + \Delta b \\ \beta_0 = \beta + \Delta \beta \end{cases} \quad (27)$$

where m_c is the membership degree, T^* is a fuzzy set, and q is the number of elements in the fuzzy set.

4.2. Analysis of Results

MATLAB/Simulink is used to verify the stability and performance of Fuzzy-ADRC regarding the output voltage of the PEMFC, where a PEMFC with the specifications described in Section 2.2.1 is again selected.

The experimental operating conditions are set as follows: The load current is maintained at 2.5 A for the first 100 s and then abruptly changed to 4 A at 100 s, after which it is subsequently shifted to 1 A at 200 s. Appropriate parameters are configured for the controller to observe the variations in the output voltage of the PEMFC. Figure 18 presents a comparison of the dynamic response of the PEMFC's output voltage to step changes in the load current, both with and without the controller in place, under the given load step changes.

**Figure 18.** Dynamic response curves of the PEMFC output voltage (comparison of curves with and without Fuzzy-ADRC).

In the absence of the controller, the output voltage decreases as the load current increases; this is due to the conversion of the energy consumed via the internal resistance of the PEMFC into thermal energy with the increasing load current. Based on the experimental results, the simulated structural curves of the output voltage closely match the calculated values, confirming the feasibility of this dynamic model for control purposes. After incorporating the controller, when the load current experiences abrupt changes, the output voltage exhibits corresponding small downward or upward oscillations within a short period, subsequently recovering and stabilizing at the set value after some time. This occurs because the controller captures and calculates the output value and disturbance changes in real time, feeding back the observations to the input, thereby enhancing the system's disturbance resistance and robustness. Additionally, the ESO within the controller accurately tracks the system's state, with its voltage tracking value (V1) closely aligning with the output voltage waveform (V), achieving the real-time observation of the output voltage and confirming the excellent tracking performance of the Fuzzy-ADRC method.

In order to illustrate the control effectiveness of Fuzzy-ADRC, we compare PID control, ADRC control, and Fuzzy-ADRC. A comparison of the output voltage curves of the PEMFC system under these three control strategies is shown in Figure 19.

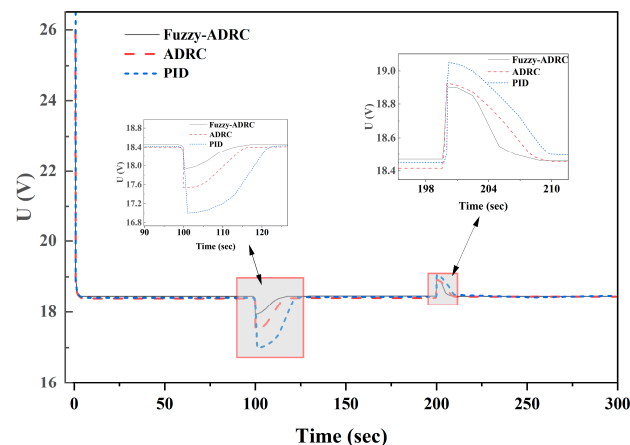


Figure 19. Comparison of PID, ADRC, and Fuzzy-ADRC control effects.

The simulation results reveal that all three controllers exhibit a certain degree of overshoot when subjected to sudden changes in the load current. Specifically, during the current increase at 100 s, the results are as follows.

Under PID control, the output voltage overshoot is approximately 8.10%, returning to the set value of 18.5 V after approximately 27 s. Under ADRC control, the output voltage overshoot is approximately 5.41%, recovering to the set value after approximately 18 s. Under Fuzzy-ADRC control, the output voltage overshoot is approximately 2.16%, reverting to the set value within approximately 9 s.

Similarly, during the current decrease at 200 s, under PID control, the output voltage overshoot is approximately 4.86%, returning to the set voltage of 18.5 V after approximately 10 s. Under ADRC control, the output voltage overshoot is approximately 3.78%, recovering to the set value after approximately 8 s. Under Fuzzy-ADRC control, the output voltage overshoot is approximately 3.24%, returning to the set value within approximately 5 s.

The control strategy proposed in this section demonstrates the smallest overshoot and the fastest adjustment time in the closed-loop system under the same external disturbances. It exhibits extremely high dynamic stability when encountering load disturbances and significantly improves the system's robustness compared to traditional controllers.

5. Conclusions and Future Work

This study focused on PEMFC applications at low temperatures within an SOS in Antarctica. By leveraging the mechanism-based modeling of a PEMFC's internal multi-physical fields and conducting low-temperature experiments, the optimal operating conditions for PEMFCs under varying external temperatures were determined. Specifically, the PEMFC exhibited the optimal output performance with a voltage of 14.7 V and a stack internal temperature of 328.15 K under a load current of 1.7 A, an ambient temperature of 293.15 K, and an RH of 60%. Additionally, at 268.15 K, the PEMFC's open-circuit voltage peaked at 35 V, indicating that low-temperature environments are conducive to heat dissipation in air-cooled PEMFCs. A temperature coordination control strategy for a 30 W PEMFC power generation system was designed for an external temperature of 253.15 K, and it was verified through experiments. This strategy enabled the PEMFC's internal temperature to swiftly reach the optimal operating temperature point, enhancing its output performance. Finally, based on the low-temperature operation control strategy, a Fuzzy-ADRC method was proposed to optimize the input parameter gain ratio, and the PEMFC's output voltage was found to rapidly reach the target value under step loads. Comparing the stabilizing effects of three controllers on the output voltage at 100 s and 200 s, the proposed Fuzzy-ADRC exhibited an overshoot of only 2.16% and 3.24%, respectively, and rapidly returned to the set value within 9 s and 5 s, outperforming the other two controllers.

After being subjected to rigorous simulations and low-temperature experiments, the PEMFC control system discussed in this work has been deployed and is operational within the microgrid system of China's SOS in Antarctica. It is capable of providing stable and reliable electrical power to various meteorological observation units within the SOS, adhering to the energy management strategy of the microgrid system. During China's 41st Antarctic Research Expedition in 2024, a PEMFC system with a capacity of hundreds of kilowatts will be installed and commissioned at Qinling Station. Based on the system's on-site performance during this period, future research endeavors will further investigate and ascertain the operational reliability of PEMFC systems at coastal stations in Antarctica.

Author Contributions: Conceptualization, J.W. and G.Z.; methodology, Y.D.; software, J.W. and G.Z.; validation, Y.D.; formal analysis, J.W.; investigation, B.F.; writing—original draft preparation, J.W.; visualization, Y.X.; project administration, B.F.; funding acquisition, Y.D. and G.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Key Research and Development Program of China, grant number 2021YFC2803304, the funder Guangyu Zuo; the National Natural Science Foundation of China, grant number U23A20649, 42306260, the funder Guangyu Zuo; the China Postdoctoral Science Foundation, grant number 2023M733042, the funder Guangyu Zuo; the Applied Basic Research Project of Shanxi Province, grant number 20210302124318, the funder Guangyu Zuo; the Scientific and Technological Innovation Programs of Higher Education Institutions in Shanxi, grant number 2021L025, the funder Guangyu Zuo; and the Shanxi Provincial Key Research and Development Project, grant number 202102060301020, the funder Yinke Dou.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data that support the findings of this study are available from the corresponding authors upon reasonable request.

Acknowledgments: The authors thank the Polar Research Institute of China for supporting the field data collection.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Dou, Y.K.; Zuo, G.Y.; Chang, X.M.; Chen, Y. A Study of a Standalone Renewable Energy System of the Chinese Zhongshan Station in Antarctica. *Appl. Sci.* **2019**, *9*, 1968. [\[CrossRef\]](#)
2. Zuo, G.Y.; Dou, Y.K.; Wang, J.; Yang, B.; Kou, L.W. A Multi-Objective Scheduling Strategy for a Hybrid Energy System for Antarctic Coastal Research Stations. *J. Mar. Sci. Eng.* **2024**, *12*, 781. [\[CrossRef\]](#)
3. Wang, J.; Dou, Y.K.; Zuo, G.Y.; Lan, M.S.; Chang, X.M.; Yang, B.; Du, Z.H.; Yu, M.Y.; Mao, Q.Y. Application and effect analysis of renewable energy in a small standalone automatic observation system deployed in the polar regions. *AIP Adv.* **2022**, *12*, 125218. [\[CrossRef\]](#)
4. Zuo, G.Y.; Dou, Y.K.; Chang, X.M.; Chen, Y. Design and Application of a Standalone Hybrid Wind–Solar System for Automatic Observation Systems Used in the Polar Region. *Appl. Sci.* **2018**, *8*, 2376. [\[CrossRef\]](#)
5. Blal, M.; Belasri, A.; Benatillah, A.; Hamouda, M.; Lachtar, S.; Sahouane, N.; Laribi, S.; Mostefaoui, M. Assessment of solar and wind energy as motive for potential hydrogen production of Algeria country; development a methodology for uses hydrogen-based fuel cells. *Int. J. Hydrogen Energy* **2018**, *43*, 9192–9210. [\[CrossRef\]](#)
6. Datta, B.K.; Velayutham, G.; Prasad Goud, A. Fuel cell power source for a cold region. *J. Power Sources* **2002**, *106*, 370–376. [\[CrossRef\]](#)
7. Russia and South Korea Will Cooperate to Build an Emission-Free Arctic Research Station Using Hydrogen Fuel. Global Hydrogen Energy Network—New Energy Network Synthesis. 2020. Available online: www.china-nengyuan.com (accessed on 24 December 2024).
8. Participate in the Construction of “Snowflake” Station! China and Russia will Soon Sign Cooperation on an Arctic Hydrogen Station. Distributed Energy Website. 2023. Available online: www.chinaden.cn (accessed on 24 December 2024).
9. The Clean Energy System of Taiyuan University of Technology Has Generated the First Electricity in Antarctica. *Shanxi Daily*. 2024. Available online: <http://epaper.sxrb.com/shtml/sxrb/20240102/937223.shtml> (accessed on 24 December 2024).
10. Taiyuan University of Technology Polar Clean Energy Team to Antarctica. *Shanxi Daily*. 2024. Available online: <http://epaper.sxrb.com/shtml/sxrb/20241030/1023149.shtml> (accessed on 24 December 2024).
11. Nivolianiti, E.; Karnavas, Y.L.; Charpentier, J.F. Fuzzy Logic-Based Energy Management Strategy for Hybrid Fuel Cell Electric Ship Power and Propulsion System. *J. Mar. Sci. Eng.* **2024**, *12*, 1813. [\[CrossRef\]](#)
12. Truong, H.V.A.; Do, T.C.; Dang, T.D. Enhancing Efficiency in Hybrid Marine Vessels through a Multi-Layer Optimization Energy Management System. *J. Mar. Sci. Eng.* **2024**, *12*, 1295. [\[CrossRef\]](#)
13. Jung, W.; Chang, D. Deep Reinforcement Learning-Based Energy Management for Liquid Hydrogen-Fueled Hybrid Electric Ship Propulsion System. *J. Mar. Sci. Eng.* **2023**, *11*, 2007. [\[CrossRef\]](#)
14. Jiao, K.; Li, X. Effects of various operating and initial conditions on cold start performance of polymer electrolyte membrane fuel cells. *Int. J. Hydrogen Energy* **2009**, *34*, 8171–8184. [\[CrossRef\]](#)
15. Min, H.; Cao, Q.; Yu, Y.; Zhang, Z.; Lin, J. A cold start mode of proton exchange membrane fuel cell based on current control. *Int. J. Hydrogen Energy* **2022**, *47*, 5507–5520. [\[CrossRef\]](#)
16. Amamou, A.; Kandidayeni, M.; Boulon, L.; Kelouwani, S. Real time adaptive efficient cold start strategy for proton exchange membrane fuel cells. *Appl. Energy* **2018**, *216*, 21–30. [\[CrossRef\]](#)
17. Amamou, A.; Kandidayeni, M.; Kelouwani, S.; Boulon, L. An Online Self Cold Startup Methodology for PEM Fuel Cells in Vehicular Applications. *IEEE Trans. Veh. Technol.* **2020**, *69*, 14160–14172. [\[CrossRef\]](#)
18. Zhan, Z.G.; Yuan, C.; Hu, Z.R.; Wang, H.; Sui, P.C.; Djilali, N.; Pan, M. Experimental study on different preheating methods for the cold-start of PEMFC stacks. *Energy* **2018**, *162*, 1029–1040. [\[CrossRef\]](#)
19. Fang, C.; Xu, L.F.; Cheng, S.L.; Li, J.Q.; Jiang, H.L.; Ouyang, M.G. Sliding-mode-based temperature regulation of a proton exchange membrane fuel cell test bench. *Int. J. Hydrogen Energy* **2017**, *42*, 11745–11757. [\[CrossRef\]](#)
20. Ko, J.; Ju, H. Comparison of numerical simulation results and experimental data during cold-start of polymer electrolyte fuel cells. *Appl. Energy* **2012**, *94*, 364–374. [\[CrossRef\]](#)
21. Gwak, G.; Ko, J.; Ju, H. Numerical investigation of cold-start behavior of polymer-electrolyte fuel-cells from subzero to normal operating temperatures-Effects of cell boundary and operating conditions. *Int. J. Hydrogen Energy* **2014**, *39*, 21927–21937. [\[CrossRef\]](#)
22. Gwak, G.; Ju, H. A rapid start-up strategy for polymer electrolyte fuel cells at subzero temperatures based on control of the operating current density. *Int. J. Hydrogen Energy* **2015**, *40*, 11989–11997. [\[CrossRef\]](#)
23. Lin, R.; Weng, Y.M.; Lin, X.W.; Xiong, F. Rapid cold start of proton exchange membrane fuel cells by the printed circuit board technology. *Int. J. Hydrogen Energy* **2014**, *39*, 18369–18378. [\[CrossRef\]](#)
24. Zhou, Y.B.; Luo, Y.Q.; Yu, S.H.; Jiao, K. Modeling of cold start processes and performance optimization for proton exchange membrane fuel cell stacks. *J. Power Sources* **2014**, *247*, 738–748. [\[CrossRef\]](#)
25. Tabe, Y.; Saito, M.; Fukui, K.; Chikahisa, T. Cold start characteristics and freezing mechanism dependence on start-up temperature in a polymer electrolyte membrane fuel cell. *J. Power Sources* **2012**, *208*, 366–373. [\[CrossRef\]](#)

26. Lei, L.; He, P.; He, P.; Tao, W.Q. A comparative study: The effect of current loading modes on the cold start-up process of PEMFC stack. *Energy Convers. Manag.* **2022**, *251*, 114991. [\[CrossRef\]](#)
27. Gießgen, T.; Jahnke, T. Assisted cold start of a PEMFC with a thermochemical preheater: A numerical study. *Appl. Energy* **2023**, *331*, 120387. [\[CrossRef\]](#)
28. Li, L.J.; Wang, S.X.; Yue, L.K.; Wang, G.Z. Cold-start method for proton exchange membrane fuel cells based on locally heating the cathode. *Appl. Energy* **2019**, *254*, 113716. [\[CrossRef\]](#)
29. Mahjoubi, C.; Olivier, J.C.; Skander-mustapha, S.; Machmoum, M.; Slama-belkhodja, I. An Improved Thermal Control of Open Cathode Proton Exchange Membrane Fuel Cell. *Int. J. Hydrogen Energy* **2019**, *44*, 11332–11345. [\[CrossRef\]](#)
30. Li, D.Z.; Li, C.; Gao, Z.Q.; Jin, Q.B. On active disturbance rejection in temperature regulation of the proton exchange membrane fuel cells. *J. Power. Sources* **2015**, *283*, 452–463. [\[CrossRef\]](#)
31. Liu, J.; Chen, H.; Zhang, T. Analysis of cold start characteristics in a PEMFC stack with different current loading modes. *Int. J. Hydrogen Energy* **2024**, *51*, 1456–1476. [\[CrossRef\]](#)
32. Spiegel, C. *PEM Fuel Cell Modeling and Simulation Using MATLAB*; Publishing House of Electronics Industry: Beijing, China, 2013; ISBN 978-7-121-19816-8.
33. Jiao, K.; Li, X. Three-dimensional multiphase modeling of cold start processes in polymer electrolyte membrane fuel cells. *Electrochim. Acta* **2009**, *54*, 6876–6891. [\[CrossRef\]](#)
34. Yang, Z.R.; Du, Q.; Huo, S.; Jiao, K. Effect of membrane electrode assembly design on the cold start process of proton exchange membrane fuel cells. *Int. J. Hydrogen Energy* **2017**, *42*, 25372–25387. [\[CrossRef\]](#)
35. Mu, Y.T.; He, P.; Ding, J.; Tao, W. Modeling of the operation conditions on the gas purging performance of polymer electrolyte membrane fuel cells. *Int. J. Hydrogen Energy* **2017**, *42*, 11788–11802. [\[CrossRef\]](#)
36. Abdi, H.; Messaoudene, N.A.; Kolsi, L.; Belazzoug, M. Multi-objective optimization of operating parameters of a PEMFC under flooding conditions using the non-dominated sorting genetic algorithm. *Therm. Sci.* **2019**, *23*, 3525–3537. [\[CrossRef\]](#)

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.