Energy Engineering

Tech Science Press

http://doi.org/10.32604/ee.2026.085738

REVIEW

Performance Degradation Mechanisms and Mitigation Strategies for PEM Fuel Cell Systems in High-Altitude Environments

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Received: 17 May 2026; Accepted: 26 June 2026; Published: 12 November 2026

ABSTRACT: As proton exchange membrane fuel cell systems are increasingly considered for transportation and stationary power applications in high-altitude regions, their performance degradation under low-pressure and oxygen-deficient environments has become a critical barrier to practical deployment. This review summarizes the key mechanisms responsible for PEMFC performance loss under high-altitude conditions, including reduced oxygen partial pressure, aggravated activation and concentration polarization, increased compressor load, and decreased system net power. Recent progress is reviewed from the perspectives of stack materials and components, air supply subsystems, system integration, control strategies, and energy management. Particular attention is given to catalyst-layer design, bipolar plate flow-field optimization, high-pressure-ratio air compressors, turbine-assisted energy recovery, oxygen excess ratio control, and net-power optimization. The analysis indicates that the major technical challenges for high-altitude PEMFC operation are no longer limited to stack materials, but are strongly associated with the coupled optimization of air supply, flow-field design, compressor operating boundaries, and altitude-adaptive control. Future research should therefore focus on integrated material–stack–system testing platforms, long-term field validation, and predictive models that couple degradation mechanisms with system-level control. This review provides a systematic reference for the design and optimization of PEMFC systems for high-altitude applications.

KEYWORDS: Proton exchange membrane fuel cell (PEMFC); high-altitude; performance degradation; air supply system; environmental adaptability

1 Introduction

Proton exchange membrane fuel cells (PEMFCs) have attracted sustained attention as clean and efficient electrochemical energy conversion devices because of their zero-emission operation, high power density, high energy conversion efficiency, and rapid start-up capability [1,2]. Their wide power range, from watt-level portable devices to megawatt-scale stationary systems, makes them suitable for diverse applications, including vehicle propulsion, distributed power generation, and portable power supply.

In recent years, considerable progress has been made in PEMFC technology, particularly in power density [3], dynamic response [4], durability and degradation mitigation [5], start–stop operation [6], and low-temperature adaptability [7]. These advances have supported the demonstration and deployment of

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PEMFC systems in low-altitude regions. However, their operation in high-altitude areas, especially the plateau regions of western China, still faces substantial challenges [8]. As altitude increases, atmospheric pressure and air density decrease, which directly reduces the oxygen partial pressure and the oxygen mass flow available for the cathodic oxygen reduction reaction. This low-pressure and oxygen-deficient environment can aggravate oxygen starvation, increase polarization losses, and reduce stack output performance. In addition, high-altitude regions are often associated with low temperature, low humidity, and stronger ultraviolet radiation. These environmental factors may further affect water management, material durability, and system stability. Although low-temperature operation and cold-start performance have been widely studied under winter or plain-region conditions, the coupled effects of low pressure and oxygen deficiency on PEMFC system performance, together with suitable mitigation strategies, remain less well understood.

Earlier studies on high-altitude PEMFC operation were mainly concerned with air-cooled systems and specialized applications such as unmanned aerial vehicles. These systems differ markedly from high-power liquid-cooled PEMFC systems in stack structure, power level, thermal management, auxiliary components, and operating strategy. For liquid-cooled PEMFC systems used in vehicles or stationary power generation, high-altitude operation imposes additional requirements on both the stack and the balance-of-plant. In particular, the air supply subsystem must compensate for reduced inlet air density, which often leads to higher compressor speed, increased parasitic power consumption, and a narrower operating margin. These system-level effects can be as important as the electrochemical losses occurring within the stack.

Therefore, a systematic understanding of PEMFC performance degradation in high-altitude environments requires consideration of the coupled interactions among stack materials, electrochemical reaction processes, air supply components, system integration, and control strategies. This review focuses on liquid-cooled PEMFC systems and examines their degradation mechanisms and improvement approaches under high-altitude, low-pressure, and oxygen-deficient conditions. First, the effects of reduced oxygen partial pressure on stack electrochemical behaviour, mass transport, and polarization losses are analysed. Second, the challenges faced by key system components, especially the air compressor and air supply subsystem, are discussed in relation to efficiency loss and increased auxiliary power demand. Finally, recent progress in control strategies and energy management methods for maintaining oxygen supply, improving net power output, and enhancing high-altitude adaptability is reviewed. By linking stack-level degradation with system-level constraints, this review aims to provide a clearer basis for the design and optimization of PEMFC systems for high-altitude applications.

2 High-Altitude Effects on PEMFC Performance

High-altitude environments affect PEMFC systems through both direct electrochemical effects and indirect system-level constraints. The decrease in atmospheric pressure reduces oxygen partial pressure and air density, which influences cathode reaction kinetics, mass transport, compressor operation, and ultimately the net output power of the system. Therefore, before discussing stack- and system-level degradation mechanisms, it is necessary to first clarify the main atmospheric changes associated with increasing altitude.

2.1 Atmospheric Characteristics at High Altitude

Atmospheric temperature, atmospheric pressure, and oxygen partial pressure are the most direct environmental parameters affecting PEMFC operation at high altitude. These parameters determine oxygen availability at the cathode inlet and also influence compressor operation, water management, and

heat transfer. In this review, their variation with altitude is estimated using the International Standard Atmosphere (ISA) model [9]. The specific equations are given as follows:

$$T_h = T_0 - 6.5 \times \frac{h}{1000} \tag{1}$$

$$P_h = P_0 \times \left[1 - \left(0.0065 \frac{h}{T_0}\right)\right]^{5.2561} \tag{2}$$

$$P_{O_2}^h = P_h \times 20.948\% \tag{3}$$

where T_0 is the atmospheric temperature at sea level, 288.15 K; P_0 is the atmospheric pressure at sea level, 101.325 kPa; and $p_{O_2}^h$ is the oxygen partial pressure in the atmosphere at an altitude of h meters.

The atmospheric parameters calculated at representative altitudes are listed in Table 1. As altitude increases, atmospheric temperature decreases at an approximately constant lapse rate of 6.5 K per 1000 m, while atmospheric pressure and air density decrease markedly. Although the oxygen volume fraction in dry air remains nearly constant at approximately 20.948%, the oxygen partial pressure decreases with the reduction in total atmospheric pressure [8]. As a result, for a given intake volume, the amount of oxygen supplied to the cathode decreases with altitude. This reduction in oxygen availability is a direct cause of oxygen starvation in PEMFC systems operating under high-altitude conditions.

Table 1: Atmospheric parameters at representative altitudes calculated using the International Standard Atmosphere model.

Altitude/m	Atmospheric Pressure/kPa	Atmospheric Temperature/K	Oxygen Partial Pressure/kPa
0	101.325	288.15	21.22
1000	89.88	281.65	18.83
2000	79.50	275.15	16.65
3000	70.12	268.65	14.69
4000	61.66	262.15	12.92
4500	57.75	258.90	12.10

2.2 Stack-Level Degradation Mechanisms

The reduction in oxygen partial pressure at high altitude first affects the electrochemical processes inside the fuel cell stack, especially the cathodic oxygen reduction reaction and oxygen transport through the gas diffusion layer and catalyst layer. A PEMFC system typically consists of a fuel cell stack, air supply subsystem, hydrogen supply subsystem, thermal and water management subsystem, and control subsystem. Among these, the stack is the core component responsible for electrochemical energy conversion. It is assembled from key materials and components, including the proton exchange membrane, catalyst layer, gas diffusion layer, and bipolar plates. Fig. 1 illustrates the basic transport and reaction pathways in a PEMFC, including hydrogen oxidation at the anode, proton transport through the membrane, electron transfer through the external circuit, and oxygen reduction at the cathode. Under high-altitude conditions, the cathode side is more strongly affected because the reduced oxygen partial pressure directly limits oxygen availability in the catalyst layer and gas diffusion layer.

$$H_2 + \frac{1}{2} O_2 \rightarrow H_2O \ (\mathrm{E}^0 = +1.229 \ \mathrm{V}) \tag{4}$$

Anode:

$$H_2 \rightarrow 2H^+ + 2e^- \ (E^0 = 0\ V) \tag{5}$$

Cathode:

$$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O \ (E^0 = +1.229\ V) \tag{6}$$

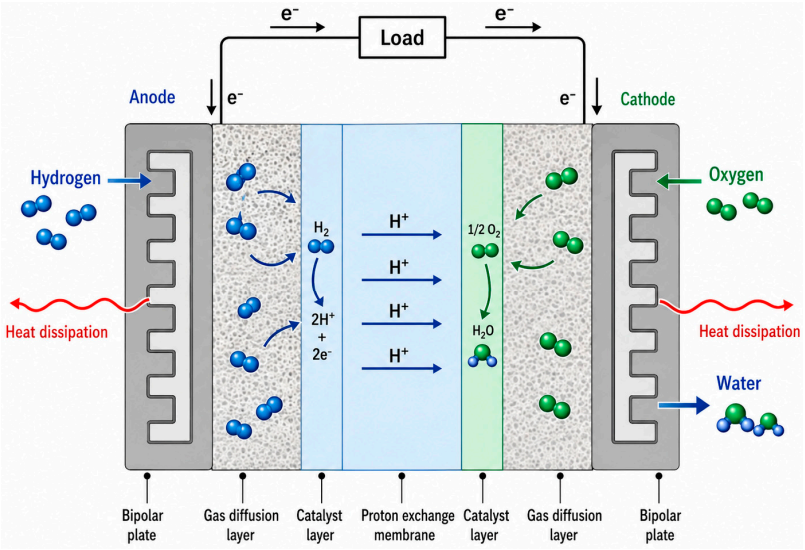


Figure 1: Schematic diagram of a PEMFC.

The electrochemical performance of a PEMFC is commonly evaluated using cell voltage and output power. Under practical operating conditions, the actual cell voltage is lower than the reversible voltage because of activation, ohmic, and concentration losses. These losses are particularly important on the cathode side, where the oxygen reduction reaction is kinetically sluggish and oxygen transport can become limiting. The output voltage of a single cell can therefore be expressed as follows:

$$\begin{cases} V_{cell} = E_{Nernst} - V_{act} - V_{ohm} - V_{con} \\ E_{Nernst} = E_0 - \frac{RT}{2F}\ln\left(\frac{\frac{P_{H_2O}}{P_0}}{\frac{P_{H_2}}{P_0}\left(\frac{P_{O_2}}{P_0}\right)^{0.5}}\right) + \frac{\Delta S_{m,298.15K}}{2F}(T - 298.15K) \\ V_{act} = \frac{RT}{\alpha F}\ln\left(\frac{i}{i_0}\right) \\ V_{ohm} = i \cdot R_{ohn} \\ V_{con} = \frac{RT}{2F}\ln\left(\frac{i_L}{i_L - i}\right) \\ i_L = \frac{nFDC_b}{\delta} \end{cases} \tag{7}$$

where E_{Nernst} is the thermodynamic electromotive force (V); E_0 is the ideal electromotive force of the fuel cell under standard conditions (1 atm and reaction temperature T) (V); F is the Faraday constant, taken as 96,485.33 C·mol^{-1}; R is the ideal gas constant, taken as 8.314 J·mol^{-1}·K^{-1}; P_{H2} is the partial pressure of H_2 at the anode (bar); P_{O2} is the partial pressure of O_2 at the cathode (bar); P_{H2O} is the partial pressure of

water vapor (bar); P_0 is the reference pressure (1 atm); T is the reaction temperature (K); $\Delta S_{m,298.15K}$ is the standard molar entropy change at the standard temperature of 298.15 K; V_{act} is the activation loss (V); V_{ohm} is the ohmic loss (V); V_{con} is the concentration polarization loss (V); i is the current density (A·cm^{-2}); i_0 is the exchange current density; i_L is the limiting current density (A·cm^{-2}), which is positively correlated with the partial pressure of the reactants; R_{ohm} is the equivalent ohmic resistance (Ω); α is the charge transfer coefficient; D is the diffusion coefficient of the reactant species (cm^2·s^{-1}); δ is the diffusion distance (cm); C_b is the bulk concentration of the reactants (mol·cm^{-3}).

Based on the atmospheric parameters listed in Table 1 and Eq. (7), the Nernst voltage at different operating temperatures and altitudes can be calculated. When the altitude increases from 0 to 4500 m, the Nernst voltage decreases by approximately 12 mV, indicating that the direct thermodynamic contribution to voltage loss is relatively limited.

The influence of altitude becomes more significant when polarization losses are considered. Activation polarization mainly occurs in the low-current-density region and is closely related to the kinetics of the oxygen reduction reaction. As altitude increases, the decrease in oxygen partial pressure lowers the oxygen concentration at the cathode catalyst surface. A higher overpotential is therefore required to maintain the same reaction rate, leading to increased activation loss.

Ohmic polarization mainly depends on membrane ionic resistance, electronic resistance, and interfacial contact resistance. It is less directly affected by atmospheric pressure than activation and concentration polarization. However, the low-humidity environment often associated with high altitude may reduce membrane hydration and indirectly increase membrane resistance.

Concentration polarization becomes dominant in the high-current-density region. Its magnitude is closely related to the limiting current density i_L, which depends on the reactant concentration and mass transport capability. As altitude increases, the decrease in oxygen partial pressure reduces the bulk oxygen concentration C_b, thereby lowering i_L. Under a fixed operating current density, this leads to a more pronounced increase in concentration polarization.

In summary, the low-pressure and oxygen-deficient environment at high altitude mainly reduces stack output voltage by decreasing cathode oxygen availability, slowing oxygen reduction reaction (ORR) kinetics, and intensifying mass transport limitations. Compared with the small decrease in Nernst voltage, the increase in activation and concentration polarization losses is the dominant cause of stack-level performance degradation.

The aggravation of polarization losses at high altitudes is not uniformly distributed across the stack. Regarding oxygen content, significant cell-to-cell variations exist, with electrochemical reaction intensity decreasing from the center to the edges. Oxygen is concentrated at the inlet, while near the outlet side of each cell's flow field, significant dead zones are present where the oxygen molar fraction is nearly zero. Altitude elevation further exacerbates this inhomogeneity due to uneven flow distribution caused by the manifold configuration. Adequate cooling effectively improves temperature consistency but exacerbates concentration polarization [10]. Moreover, pronounced temperature non-uniformity exists within the stack, with central cells operating at higher temperatures than those at both ends, and local hot spots further dilute oxygen concentration [11]. The degradation rates of individual cells also differ significantly, with endplate cells exhibiting the most severe voltage decay [12].

2.3 System-Level Degradation Mechanisms

In addition to stack-level voltage losses, high-altitude operation also affects PEMFC performance at the system level by increasing auxiliary power consumption, particularly in the cathode air supply subsystem.

Fig. 2 shows a typical liquid-cooled hydrogen-air PEMFC system, which consists of the stack, air supply subsystem, hydrogen supply subsystem, thermal and water management subsystem, and control subsystem. The relationship among stack output power, auxiliary power consumption, and net system output power is given by Eq. (8) [13].

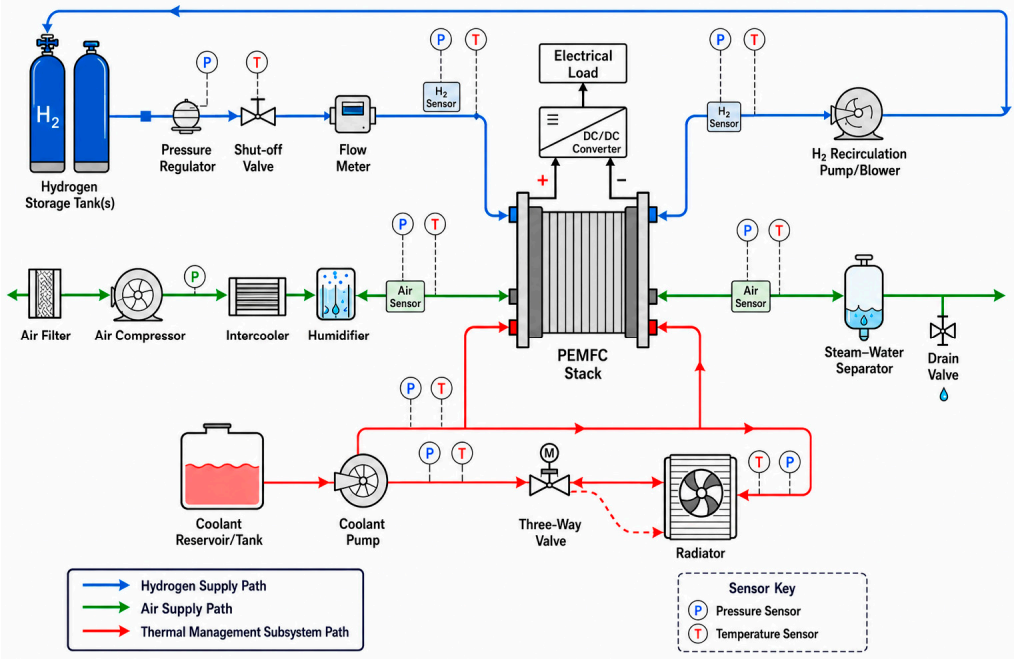


Figure 2: Schematic diagram of a typical liquid-cooled PEMFC system.

As shown in the Figure, the air supply subsystem is directly connected to cathode oxygen delivery and is therefore the most altitude-sensitive part of the balance-of-plant. At high altitude, reduced inlet air density forces the compressor to operate at a higher pressure ratio, which increases parasitic power consumption and reduces the net system output.

$$\begin{cases} P_{net} = P_{\text{stack}} - P_{cp} - P_{H_2} - P_{pump} - P_{FCU} \\ P_{\text{stack}} = V_{cell} \times i \\ P_{cp} = \tau_{cp} \cdot \omega_{cp} = \dfrac{C_p T_{cp,in}}{\eta_{cp}} \left[\left(\dfrac{P_{sm}}{P_{cp,in}} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right] m_{cp} \\ P_{pump} = \dfrac{\rho g H Q}{\eta_{pump}} \end{cases} \tag{8}$$

where P_{net} is the net output power of the system (W); P_{stack} is the power generated by the electrochemical reactions in the stack (W); P_{cp} is the power consumed by the air supply subsystem (W); P_{H2} is the power consumed by the hydrogen supply subsystem (W); P_{pump} is the power consumed by the thermal and water management subsystem (W); P_{FCU} is the power consumed by the control subsystem (W); V_{cell} is the single cell voltage (V); i is the stack current (A); τ_{cp} is the torque of the air compressor (N·m); ω_{cp} is the angular speed of the air compressor (rad/s); C_p is the specific heat capacity of air; η_{cp} is the mechanical efficiency of the air compressor; $T_{cp,in}$ is the inlet temperature of the air compressor; P_{sm} is the internal pressure of the supply pipeline; $P_{cp,in}$ is the ambient pressure; γ is the ratio of specific heat at constant pressure to that at

constant volume (γ = 1.4 under standard atmospheric conditions); m_{cp} is the mass flow rate of the gas at the compressor outlet; ρ is the density of the coolant; g is the gravitational acceleration; H is the pump head; Q is the volumetric flow rate of the coolant; η_{pump} is the pump efficiency.

For hundred-kilowatt-class fuel cell systems, auxiliary power consumption typically accounts for 20%–30% of the stack output power [14]. Among the auxiliary components, the air compressor is usually the largest power consumer, accounting for more than 80% of the total auxiliary power demand [15]. When a fuel cell engine or stationary power generation system operates at high altitude, maintaining the required stack output depends on a sufficient supply of both hydrogen and oxygen. The hydrogen supply subsystem is generally fed by a high-pressure hydrogen tank through a pressure regulation device, and is therefore less directly affected by ambient pressure than the cathode air supply subsystem. The power consumption of the control unit is relatively small and can usually be neglected in altitude-related performance analysis. The thermal and water management subsystem may also be influenced by changes in ambient temperature, air density, and heat rejection conditions, but its contribution to altitude-induced power loss is generally less dominant than that of the air supply subsystem. By contrast, the cathode air supply subsystem is strongly affected by high-altitude conditions. As ambient pressure and air density decrease, the compressor must operate at a higher pressure ratio and often at a higher rotational speed to provide the cathode pressure and oxygen mass flow required by the stack. This increases compressor power consumption and may push the compressor closer to its operating limits, such as surge or overspeed boundaries. Therefore, under high-altitude conditions, optimizing the cathode air supply strategy is essential for maintaining sufficient oxygen supply, reducing parasitic power consumption, and improving the net output power and operational stability of the fuel cell system.

3 Stack Materials and Component Design for High-Altitude Operation

3.1 Catalyst and Catalyst-Layer Design

Because cathode platinum (Pt)-based catalysts in fuel cells are constantly exposed to harsh conditions characterized by strong oxidation and high voltage, their degradation rate is significantly higher than that of the anode. The sluggish kinetics of the cathodic ORR is a key factor limiting PEMFC performance improvement [16]. Under high-altitude, low-pressure, and oxygen-deficient conditions, the inherent technical contradictions of the catalyst layer are further amplified: the low oxygen partial pressure significantly worsens ORR kinetics, requiring the catalyst layer to possess higher intrinsic activity. Meanwhile, low pressure seriously hinders oxygen transport to catalyst active sites, leading to increased concentration polarization loss and requiring a more optimized mass transfer structure [17]. Therefore, developing highly active and highly stable catalysts and optimizing catalyst layer structures have become core directions for improving stack adaptability at high altitude.

Traditional Pt/C catalysts cannot satisfy the activity requirements under low-oxygen and low-pressure conditions [18]. The dissolution and migration of Pt become more severe under high-potential operating conditions, resulting in reduced catalyst stability [19]. To address this challenge, research on Pt-based catalysts is shifting from traditional Pt/C and random alloys toward atomically precise regulation. Constructing ordered intermetallic compounds or specific nanostructures can effectively lower the Pt d-band center and suppress transition metal dissolution through controllable lattice compressive strain and stable atomic arrangements, offering significant advantages in improving intrinsic ORR activity and catalytic durability [20,21].

To address reaction deterioration caused by the low-humidity environment in high-altitude regions, researchers have begun to focus on adaptive catalyst layer design. Studies have shown that properly

regulating catalyst loading and the ionomer/carbon (I/C) ratio can effectively improve water retention under low humidity [22]. Meanwhile, significant advances have been achieved in non-precious metal catalysts, especially single-atom M-N-C systems. Through coordination environment and pore structure engineering, their ORR activity in acidic media has been substantially improved, though still inferior to Pt-based benchmarks [23]. Concurrently, the introduction of ionic liquids into the M-N-C catalyst layer has emerged as an effective strategy to enhance proton/oxygen transport and suppress H_2O_2-induced degradation [24]. Collectively, these approaches provide a promising route for PEMFC operation under low-humidity high-altitude conditions.

Optimizing the microstructure of the catalytic layer is also key to improving high-altitude adaptability. Li et al. innovatively proposed a composite cathode catalyst layer design: Pt/Vulcan (I/C = 0.6) on the side adjacent to the proton exchange membrane and Pt/Ketjenblack (I/C = 0.9) on the side adjacent to the gas diffusion layer, as shown in Fig. 3. Under low-humidity conditions (25%), this design doubled the power density compared to conventional designs [25]. Ding et al. further pointed out that the performance advantages of gradient designs are highly dependent on operating humidity and the Pt/C ratio [26]. Xuan et al. established a rapid prediction method for optimal structures based on physical models, finding that gradient designs can increase peak power density by over 4% [27]. Furthermore, recent studies have focused on regulating the spatial distribution of the ionomer in the catalyst layer and the interfacial structure. By optimizing proton/oxygen transport pathways at the three-phase interface, these studies have significantly increased fuel cell power density at low platinum loadings [28,29]. These catalyst-layer microstructure optimization strategies, including gradient design to address the coupled challenges of low humidity and low pressure, interfacial regulation of the ionomer to optimize triple-phase transport pathways, and porous engineering to enhance water retention capacity, all offer viable pathways for improving PEMFC performance under high-altitude conditions.

In summary, designing catalysts at the nanoscale in an ordered way can improve the quality and lifespan of active sites, helping to overcome the kinetic limitations caused by low oxygen pressure. Meanwhile, a gradient design of the catalytic layer can optimize the local reaction environment of active sites, reducing concentration polarization losses under low-pressure conditions. These findings suggest that a 'materials-structure' synergistic optimization can partially offset the negative effects of high-altitude conditions on the catalytic layer. However, most current studies focus on dealing with a single factor (like low pressure or low humidity), and the degradation mechanisms and combined optimization strategies under conditions with low pressure, low oxygen, low humidity, and low temperature still need further exploration.

3.2 Bipolar Plate and Flow-Field Design

The flow field design of bipolar plates directly affects the transport uniformity of reactant gases to the membrane electrode assembly, water removal capability, and thermal management efficiency. Under normal pressure conditions, research on bipolar plate flow channels has made systematic progress around manufacturability, gas distribution uniformity, and flow resistance control [30–32].

Researchers worldwide have conducted extensive work on flow channel structure optimization. Wang et al. proposed a Staggered Trapezoid Baffle Plate (STBP) flow field, which forms a pressure gradient between adjacent channels to drive reactant gas to transport transversely across the rib region, significantly improving the oxygen distribution uniformity and water removal capability in the rib region, and increasing the net power density by 6.39% compared with the conventional parallel flow field [33]. Dong et al. introduced S-shaped and crescent discontinuous ribs into the flow channel, which enhanced local convection and O_2 distribution while reducing pressure drop, improving electrochemical efficiency by up to 23.61% at high

current densities [34]. Vijayakrishnan et al. proposed a sinuous flow field that enhances water removal through inter-channel diffusion and under-rib convection, achieving a 7.7% power density increase over the conventional serpentine design; moreover, a hybrid design with a serpentine anode and sinuous cathode further improved power density by 14% [35]. Xia et al. designed a leaf vein bionic flow field (LVFF) for PEMFC, and found that the 10 branch channels (BC-10) configuration achieved a 5.894% power increase over the conventional serpentine flow field (CSFF), and adding bionic streamlined blocks (CBFF) further improved the power output by 8.475% relative to CSFF, along with more uniform gas and current density distributions [36]. Choi et al. conducted an experimental study on a three-dimensional (3-D) printed non-uniformly arranged cathode flow channel, achieving a maximum power density increase of 12.8% compared with a conventional parallel flow field [37].

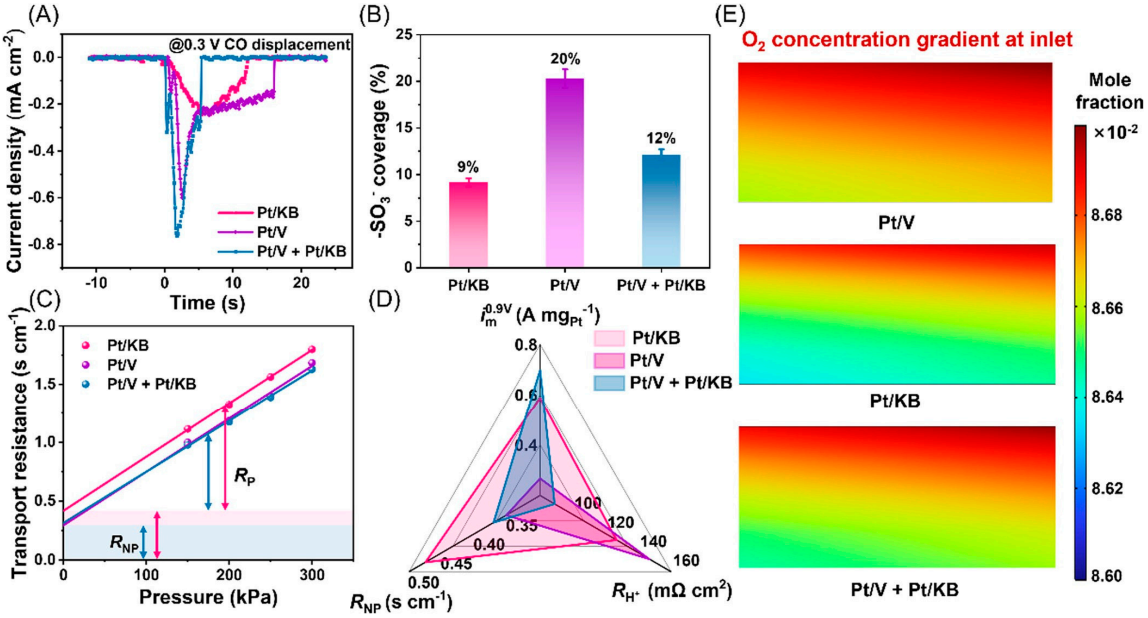


Figure 3: (**A**) CO displacement current density-time curves measured at 0.3 V versus reversible hydrogen electrode (RHE); (**B**) Sulfonate group coverage (in percent) determined from CO displacement at 0.3 V versus RHE and stripping tests; (**C**) Oxygen transport resistance as a function of total pressure in the full cell. The solid line represents the best linear fit to the four data points; (**D**) Comparison of MA, oxygen transport impedance, and proton transport for three MEAs; (**E**) Oxygen concentration gradient distribution at the inlet obtained by fuel cell single-cell simulation with a top-to-bottom orientation following the direction from GDL to PEM. Reprinted with permission from reference [25]. 2025, Siming Li; Suizhu Pei; Enyang Sun; Zhichao Liu; Jieyu Zhang; Junjie Li; Huili Chen; Haiwei Liang; Zhonghua Xiang; Min Wang; Yawei Li.

However, the changes in air physical properties caused by high altitude directly alter the flow and heat transfer behavior within the flow channels, making the bipolar plate structures optimized for plain regions prone to new issues such as uneven gas distribution, drainage difficulties, and thermal management failure under plateau environments. Consequently, in high-altitude environments, the decrease in air density and oxygen partial pressure leads to a reduction in the momentum of the reactant gas on the cathode side, and conventional flow channel designs face the following new challenges:

(1) Changes in thin-air flow characteristics: Under low Reynolds number conditions, gas flow in the channels tends more easily toward laminar flow, weakening convective oxygen transport to the diffusion layer and aggravating concentration polarization. The relative pressure drop losses of

conventional parallel and serpentine flow channels increase under low pressure, possibly leading to local oxygen deficiency.

(2) Challenges in Drainage and Water Balance: High altitudes are often accompanied by low humidity, making membranes prone to dehydration; however, water generated at the cathode under high current densities may still accumulate. An inappropriate rib-to-channel ratio in the flow channels can easily lead to a "flooding-drying" dichotomy. To address this, Peng et al. inserted porous media into the cathode flow channel, alleviating high-altitude performance degradation and increasing current density by 18.2% [38]. Though based on an air-cooled stack, its water retention-drainage coordination concept guides liquid-cooled stack design at high altitudes. Low humidity further narrows the water balance window, and the optimal rib-to-channel ratio for high-altitude conditions remains undetermined.

(3) Amplified temperature nonuniformity: Thin air makes the internal stack temperature field more sensitive to flow velocity, so the cooling channel design of bipolar plates must also address the reduced heat dissipation capability under low pressure. In addition, stronger ultraviolet radiation and larger temperature fluctuations in high-altitude regions may accelerate the ageing of externally exposed polymeric components and sealing materials, although their direct influence on internal bipolar-plate surfaces requires further clarification.

At present, research on bipolar plate flow channel optimization specifically for high-altitude environments remains almost nonexistent. Only a few Computational Fluid Dynamic (CFD) studies have begun to address this topic. Increasing channel depth (hydraulic diameter) reduces flow resistance but weakens mass transfer under the ribs, whereas segmented or bio-inspired flow channels exhibit better gas distribution uniformity at low pressures [39]. Xu et al. designed a novel mid-inlet serpentine flow channel inspired by the human heartbeat mechanism. Using 3D CFD simulation at a simulated altitude of 4000 m (0.67 atm) and a current density of 1 A/cm^2, this design increased the power density by 34.8% and, notably, improved the ionic conductivity of the membrane by 0.61 S/m compared to a conventional serpentine channel [40]. Zhao et al. applied a multi-objective optimization approach integrating CFD, response surface methodology (RSM), non-dominated sorting genetic algorithm II (NSGA-II), entropy weight method (EWM), and technique for order preference by similarity to ideal solution (TOPSIS) across altitudes from 0 to 5000 m, achieving a maximum power density increase of 19.80% (at 4000 m) and significantly improving oxygen distribution uniformity [41]. Although bio-inspired flow channels show better gas distribution uniformity under low-pressure, high-altitude conditions, their engineering application still faces two major challenges: manufacturing relies on 3-D printed, which is costly and inefficient; and different bio-inspired designs exhibit significantly different pressure drop characteristics, requiring a trade-off between low pressure drop and mass transfer efficiency [42]. Future research should focus on: (1) the quantitative relationship between flow channel geometric parameters (ridge-to-trough ratio, depth, and bend angle) and mass transfer coefficients and pressure drop at different altitudes (0~4500 m); (2) flow channel topology optimization methods that couple the multi-physics fields of heat, water, and gas within fuel cell stacks; and (3) the design and validation of 3-D printed, non-standard flow channel structures for high-altitude applications.

3.3 Stack Design and Performance Adaptability

The fuel cell stack is a strongly coupled multiphysics system involving water, heat, gas, and electricity. Its performance degradation at high altitude arises not only from changes in the intrinsic properties of materials, but also from operating conditions (inlet pressure, humidity, temperature) and matching with auxiliary systems. Existing studies have confirmed that under the same oxygen partial pressure, performance degradation caused by low total pressure is much greater than that caused by low oxygen

concentration alone, and its mechanism is the synergistic action of activation polarization and diffusion polarization [43]. Murschenhofer et al. conducted high-altitude experiments on a 120-cell liquid-cooled self-humidifying stack, demonstrating that optimized control parameters can achieve a net power gain of 29% [44]. He et al. performed CFD optimization on a 400 kW aviation liquid-cooled stack, revealing that above 4000 m altitude, uneven reactant distribution is the primary cause of performance degradation; the optimized design increases cathode catalyst layer oxygen concentration by 26.9% and reduces voltage deviation by 13.2% [45]. Nevertheless, direct system-level experimental studies on liquid-cooled stacks under high-altitude conditions remain very limited. Current research still has the following shortcomings:

(1) Lack of comparative experimental data at multiple altitudes: Most studies only simulate 0~3000 m, and direct stack performance tests above 4000 m are extremely rare. Although Liu et al. [46] observed that, in an 80 kW stack, the air compressor reached its maximum rotational speed at altitudes above 1000 m, they did not provide key data such as the internal current density distribution of the stack or local temperature variations.
(2) Neglect of stack packaging and mechanical stress effects: Under low pressure, the pressure difference inside and outside the stack decreases, which may alter the contact pressure between the bipolar plate and the membrane electrode, thereby changing contact resistance. In addition, vibration and temperature cycling during plateau transportation and operation may accelerate the aging of sealing materials, causing microleakage and further worsening operational stability under low pressure.
(3) Unclear dynamic response under transient conditions: Existing studies mostly rely on steady-state polarization curves, whereas vehicular fuel cells require frequent load changes. During altitude variation, lag in cathode pressure dynamic response may trigger transient oxygen starvation and even local voltage reversal, causing corrosion of the catalyst carbon support. There is still no lifetime degradation model for stacks under high-altitude dynamic conditions.
(4) Need to quantify the matching boundary between stack and compressor: At different altitudes, the optimal operating pressure of the stack (100~150 kPa absolute pressure) intersects with the compressor efficiency curve. Existing literature does not provide a three-dimensional map linking stack required pressure, compressor speed, and altitude.

These limitations indicate that stack performance under high-altitude conditions cannot be fully understood from steady-state polarization curves alone. Future work should develop integrated stack–system testing platforms capable of reproducing pressure, temperature, humidity, and load variations. Such platforms should enable simultaneous monitoring of local current density, high-frequency resistance, temperature distribution, water transport behavior, and compressor operating state. The resulting data would provide a stronger basis for data-driven models of stack degradation and stack–compressor matching under high-altitude conditions.

3.4 Air Supply Subsystem and Compressor Technologies

The decrease in atmospheric pressure and oxygen partial pressure at high altitude leads to insufficient oxygen mass flow at the PEMFC cathode inlet, which is one of the main causes of stack performance degradation. Simply increasing compressor speed can increase intake flow to some extent, but limited by the inherent characteristics of the compressor, such as surge boundaries and rotor dynamic limits, the dynamic response of the air supply subsystem becomes significantly slower under high-altitude and variable-load conditions, making oxygen starvation likely [47]. Therefore, optimizing the structural design and control mode of the air supply system to enhance its adaptability to high-altitude environments is

key to preventing output performance degradation and reducing compressor power consumption. Fig. 4 compares representative air-path architectures used to reduce compressor power demand, including a conventional e-compressor, a coupled e-turbo, and a decoupled e-turbine configuration. This comparison highlights that energy recovery from the cathode exhaust can partly offset the increased compressor load under high-altitude operation.

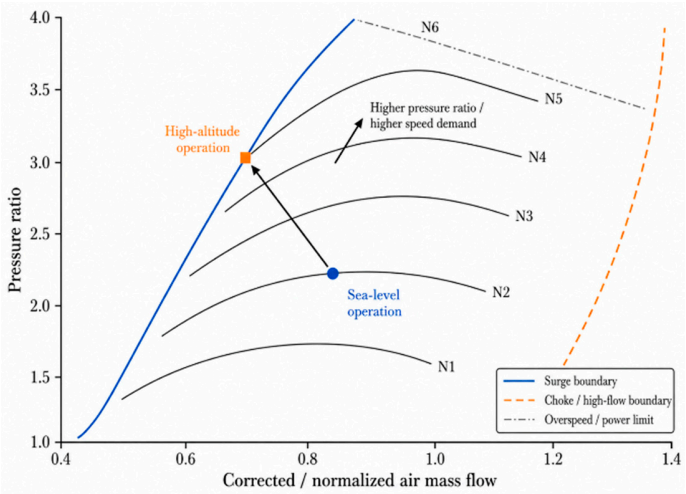


Figure 4: Schematic compressor performance map illustrating the qualitative shift of the operating point under high-altitude PEMFC operation. Reprinted with permission from reference [47]. 2022, Jonas Schröter; Daniel Frank; Valentin Radke; Christiane Bauer; Josef Kallo; Caroline Willich.

Under high-altitude conditions, to maintain the target cathode pressure and mass flow required by the stack, the compressor must provide a higher pressure ratio and speed. Centrifugal compressors, owing to their advantages of high power density, oil-free lubrication, and low vibration, have become the mainstream choice for vehicular PEMFC air supply systems. Fig. 4 illustrates the shift of the compressor operating point under high-altitude PEMFC operation. As altitude increases, the reduced inlet pressure and air density require the compressor to deliver a higher pressure ratio and operate at a higher rotational speed to maintain the target cathode air supply. Consequently, the operating point tends to move toward the surge boundary and the overspeed/power-limit region, reducing the stable operating margin of the air-supply system. Sun et al. through thermodynamic modeling comparisons, demonstrated that turbo-compressors with energy recovery are significantly superior to single-stage and two-stage centrifugal compression schemes in controlling parasitic power consumption, achieving a system exergy efficiency 4.34% higher than that of the single-stage and two-stage centrifugal compressor configuration [48]. In contrast, single-stage centrifugal compressors are highly prone to surge under conditions of high pressure ratio and low flow rate, and their stable operating range is limited, making it difficult to meet the requirements of high-altitude environments. To address this issue, two-stage centrifugal compression schemes have been proposed. By connecting two impellers in series, a higher total pressure ratio can be achieved while also expanding the stable operating range to some extent, although the additional power consumption is significant. Therefore, for air supply systems operating in high-altitude environments, two-stage compression or turbo-compression with energy recovery represents a more favorable technical choice, offering a better balance between pressure lift capability, stable operating margin, and parasitic power consumption. Martinez-Boggio et al. quantified the system-level performance of three air path layouts: e-compressor, coupled e-turbo, and decoupled e-turbo, as shown in Fig. 5, the coupled e-turbo was identified as the optimal configuration, achieving a

10% improvement in net system power at high loads [49]. It is identified that the coupled e-turbo is the optimal configuration for fuel cell systems in high-altitude environments.

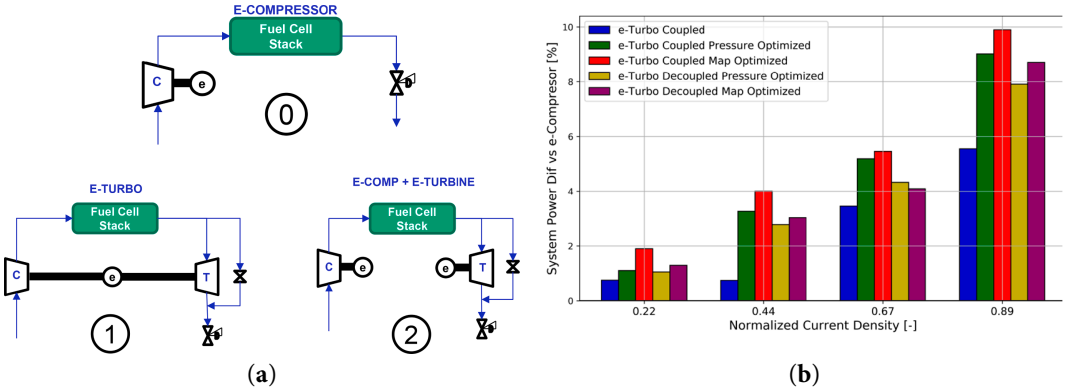


Figure 5: (**a**) Three air path architectures: E-COMPRESSOR, COUPLED E-TURBO, and DECOUPLED E-TURBINE; (**b**) System power difference between all the air path architectures with different optimization against baseline e-compressor case at four different current request conditions. Reprinted with permission from reference [49]. 2023, Santiago Martinez-Boggio; Davide Di Blasio; Tom Fletcher; Richard Burke; Antonio García; Javier Monsalve-Serrano.

3.5 System Integration under High-Altitude Conditions

Many scholars have carried out experimental and simulation studies on the overall performance of fuel cell systems under high-altitude conditions and have clarified the restrictive effect of insufficient air supply on system performance. The performance changes of fuel cell hybrid vehicles with altitude increasing from 0 m to 3000 m were simulated, and it was found that nearly 40% of the net output power of the fuel cell system was consumed by the compressor at 3000 m [50]. Chen et al. analyzed the sensitivities of cathode air excess coefficient and pressure coefficient of vehicular fuel cell systems at altitudes of 2000 m, 2800 m, 3500 m, and 4200 m. The study showed that as altitude increases, thin air and reduced oxygen partial pressure significantly degrade stack performance, and system efficiency can rapidly fall below 40% above 4000 m [51]. It was also proposed that when high pressure and high excess ratio cannot be satisfied simultaneously, priority should be given to maintaining a higher air excess ratio to improve stack operational uniformity and performance.

Liu et al. conducted steady-state and dynamic tests on a fuel cell engine test bench with altitude simulation capability. The results show that at a constant current of 230 A, when the simulated altitude exceeded a certain threshold, the compressor speed reached its upper limit; as altitude continued to increase, insufficient air intake caused the power output to decline by more than 40% [46]. Wang et al. investigated the adaptability of a 36 kW vehicular fuel cell system at an altitude of 2900 m. The results indicate that due to compressor performance limitations, the system output power experienced significant degradation. At an altitude of 3000 m, the stack power decreased by approximately12.9%, and the system power decreased by approximately 11.8%. Meanwhile, the power consumption share of auxiliary components (primarily the compressor) increased from 15%~20% under plain conditions to 20%~25% [17].

These studies confirm from an engineering application perspective that insufficient air supply is the core bottleneck restricting the power output of fuel cell engines in high-altitude environments. Increasing intake pressure and air flow can improve fuel cell output performance, especially in the high-current operating region where concentration polarization can be effectively reduced.

4 Control and Energy Management Strategies

The mechanisms discussed above show that high-altitude operation affects PEMFC systems through both cathode oxygen limitation and increased air supply demand. As altitude increases, the decrease in atmospheric pressure and oxygen partial pressure reduces compressor inlet density and cathode oxygen availability. This can intensify concentration polarization, reduce stack voltage, and in severe cases lead to transient oxygen starvation or local voltage reversal. At the same time, the compressor must operate at a higher pressure ratio and rotational speed, increasing parasitic power consumption. The absolute pressure at the cathode and anode inlets in PEMFC system designs is typically maintained at a constant level. Changes in altitude alter the pressure ratio of the air compressor rather than the internal pressure of the stack, so the transmembrane pressure difference remains stable. Operation at high altitudes generally does not compromise the mechanical integrity of the proton exchange membrane; however, coordinated gas management between the cathode and anode remains critical. This section reviews control and energy management strategies for high-altitude PEMFC systems, with emphasis on air supply control, oxygen excess ratio regulation, compressor operating limits, and net power optimization.

4.1 Air Supply Control Strategies

The structural improvement of key components provides a hardware foundation for high-altitude PEMFC systems. However, the dynamic characteristics of auxiliary components such as the air compressor and turbo-expander become considerably more intricate under high-altitude conditions. Owing to their inherent physical inertia, these components cannot ensure instantaneous balance between air supply and demand solely through hardware-based configurations during abrupt load transients and altitude variations. Currently, air subsystem control strategies are predominantly tailored to plain-level operating conditions, with a primary focus on mitigating concentration polarization at high current densities. These strategies typically employ optimization of the excess oxygen ratio, inlet pressure regulation, and coordinated feedforward-feedback control to enhance air delivery capacity, delay the onset of concentration polarization, and thereby improve peak power output.

4.1.1 PID-Based Control Strategies

Proportional-Integral-Derivative (PID) control has been widely used in PEMFC air supply systems because of its simple structure, strong robustness, and ease of engineering implementation. Its variants mainly include fuzzy PID, adaptive PID, Fuzzy-Feedforward PID, Model Predictive Control (MPC) and PID combined control, and optimal PID. Tang et al. proposed an adaptive fuzzy PID controller for oxygen excess ratio (OER) control. Under sudden load current changes, this controller can quickly stabilize OER and effectively improve net system output power [52]. Beirami et al. applied a fuzzy logic feedforward and filtered PID feedback control strategy optimized by self-adaptive differential evolution (SaDE) to regulate the OER for the PEMFC, achieving maximum net power tracking and preventing oxygen starvation [53]. Chen et al. established a PEMFC dynamic model for OER control and proposed a fractional-order PID control strategy, which outperformed traditional PID control in both control accuracy and response speed [54]. Yang et al. compared the control performances of optimal PID, Fuzzy PID, Sliding Mode Control, and Model Predictive Control under typical variable-load conditions, and the results showed that the optimal PID controller had the best overall performance in resistance to oxygen starvation, dynamic response, and internal stack state regulation [55]. However, most PID-based strategies have been developed and validated under low-altitude or simplified operating conditions. Their robustness under rapid ambient-

pressure variation, reduced compressor inlet density, and compressor operating constraints still needs further investigation.

4.1.2 Sliding Mode Control Strategies

Sliding Mode Control (SMC) has the advantages of not depending strongly on controlled-object parameters, fast response, strong robustness, high stability, and low computational complexity, making it suitable for controlling PEMFC air systems with parameter uncertainty under high-altitude conditions. Commonly used SMC strategies in PEMFC air system control include conventional SMC, second-order sliding mode, super-twisting algorithms, adaptive super-twisting, and composite sliding mode control. Silaa et al. proposed quasi-continuous high-order sliding mode control (QC-HOSM), and experiments showed that compared with traditional SMC, QC-HOSM can reduce chattering by 84% and significantly improve system power output [56]. Although this study focused on overall power system regulation, the effectiveness of its high-order sliding mode algorithm in chattering suppression provides a valuable methodological reference for the design of air-feed system control strategies under high-altitude conditions. Furthermore, Silaa et al. developed a sliding mode controller with a quick power reaching law (SMCPRL). Compared with the super-twisting algorithm, this controller achieved faster response, better tracking accuracy, and greater robustness, while also reducing system power consumption and improving efficiency. Its feasibility and effectiveness were validated through both simulation and real-time experiments [57]. Compared with PID control, SMC strategies are more complex, but their robustness against parameter uncertainty makes them attractive for high-altitude PEMFC operation. For practical application, however, SMC-Based controllers still need to be evaluated together with compressor safety limits, sensor delays, and transient oxygen starvation constraints.

4.1.3 Model Predictive Control Strategies

Model Predictive Control (MPC) determines optimal control inputs by predicting future system behavior and solving an optimization problem at each time step, making it suitable for multi-constraint, nonlinear PEMFC air supply systems. Improved forms of MPC include Nonlinear MPC, Multi-Model MPC, Hierarchical MPC, Neural-Network MPC, and their composite control strategies. Fu et al. proposed feedforward model predictive control to compensate in advance for load changes, maintaining stable OER tracking even under rapid variable-load conditions [58]. Yang et al. introduced sliding mode control into the MPC framework and proposed a sliding mode predictive control method, which takes the sliding surface of the tracking error as the prediction object and solves the optimal control law through rolling optimization. This method not only retains the ability of MPC to handle multiple constraints but also enhances nonlinear adaptability and robustness by leveraging sliding mode control [59]. Chen et al. proposed a dual-loop control structure: the inner loop uses Feedback-Linearization-Based MPC to control compressor flow, while the outer loop tracks the optimal OER trajectory using disturbance rejection strategies to achieve maximum net output power. At the same time, an observer is used to rapidly reconstruct OER, overcoming the effects of sensor lag and measurement errors [60]. Chen et al. further developed an adaptive model predictive control approach that updates the system model in response to variations in altitude and load, and actively prevents compressor surge under extreme altitude-gradient conditions, with its effectiveness validated through hardware-in-the-loop experiments conducted in high-altitude environments [61]. This work also highlights the importance of coordinated anode–cathode gas management under variable-altitude operation, as stable cathode oxygen supply must be matched with reliable anode pressure regulation to maintain overall stack safety and performance. Compared with PID and SMC-Based methods, MPC is better suited to handling

multivariable constraints, which is particularly important when altitude variation simultaneously changes cathode pressure demand, oxygen excess ratio, anode pressure regulation, and compressor operating boundaries.

Fig. 6 shows a typical SM-MPC control structure, in which the predictive model, observer, sliding surface, and rolling optimization are combined to determine the compressor and valve control inputs. Such a structure is relevant to high-altitude operation because it can explicitly handle oxygen excess ratio tracking, cathode pressure regulation, and compressor operating constraints.

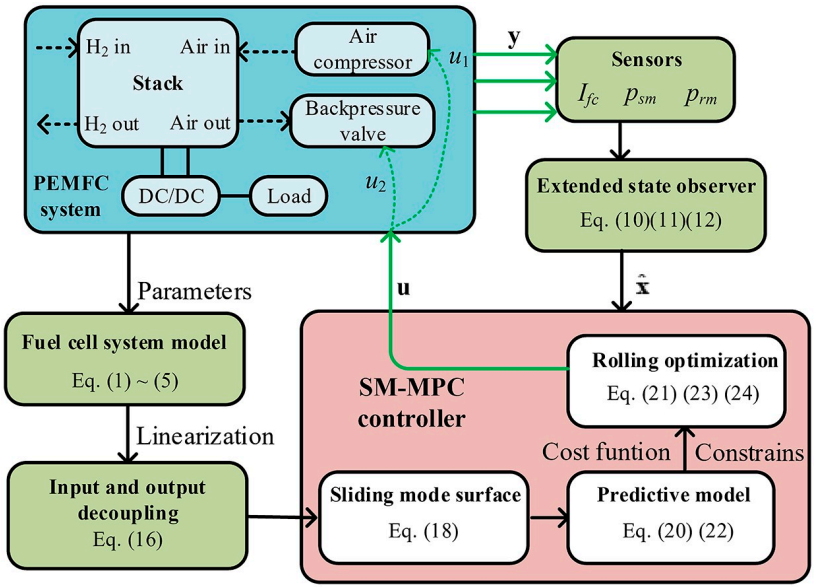


Figure 6: Block diagram of fuel cell air system control based on sliding mode predictive control. Reprinted with permission from reference [59]. 2024, Duo Yang; Hanwen Fu; Junjun Li; Siyu Wang.

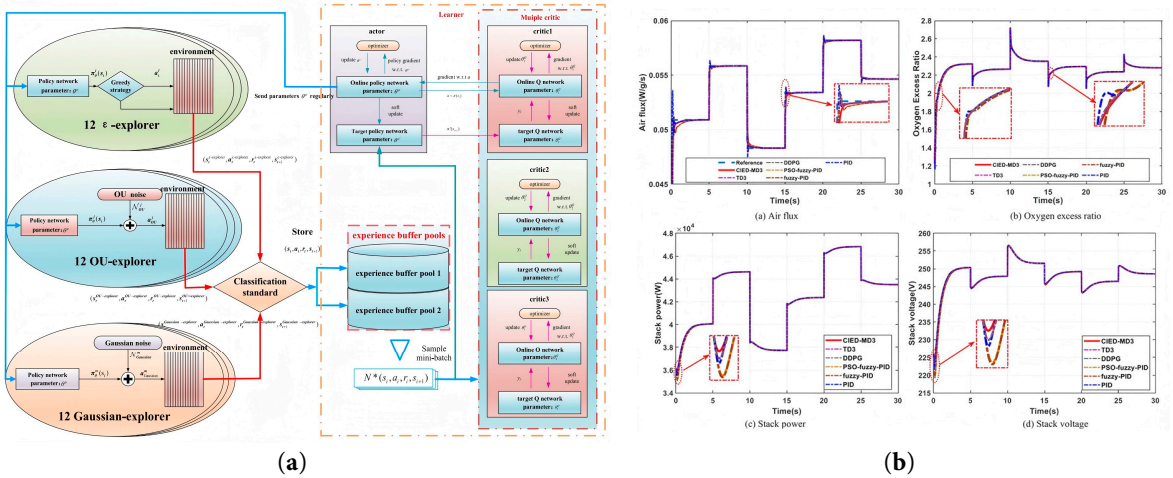
4.1.4 Pressure-Flow Decoupling Control

The core objective of both PID-based composite control and robust nonlinear strategies such as sliding mode control (SMC) is to maintain the oxygen excess ratio (OER) within a reasonable range. However, there is strong coupling between air pressure and flow, and as ambient pressure decreases, fuel cell performance becomes significantly more sensitive to supply pressure. Traditional control strategies therefore find it difficult to achieve precise coordinated control of both variables. To address this issue, decoupling control strategies have been proposed to improve rapid response capability and control accuracy.

Qiu et al. proposed a control method based on data-driven modeling and optimized diagonal matrix decoupling to address airflow-pressure coupling in the air supply system of fuel cell vehicles, achieving independent control of airflow and pressure. Experiments showed that compared with conventional decoupling control, the standard deviations of airflow and pressure control errors were reduced by 9.7% and 14.4%, respectively [62]. Peng et al. proposed a coordinated control method based on feedback-linearization sliding mode decoupling and fuzzy anti-surge compensation for airflow-pressure coupling and compressor surge, and experiments showed that this method can effectively achieve decoupled tracking while avoiding compressor surge under load fluctuations [63]. With the development of artificial intelligence, reinforcement learning has also been introduced into decoupling control to enhance adaptability to nonlinear systems. Li et al. proposed a Collective Intelligence Exploration Distributed Multi-delay Deep Deterministic Policy Gradient (CIED-MD3) intelligent control algorithm based on distributed deep reinforcement learning. Through

multi-agent collaborative exploration and full interaction with the environment, the algorithm achieves precise and rapid control of air flow under load addition/shedding and random disturbance conditions, exhibiting better response speed and robustness than traditional PID and fuzzy PID controllers [64].

Fig. 7 illustrates how distributed reinforcement learning can be used to train an intelligent PEMFC air-supply controller and improve airflow response under random load disturbances. Although such frameworks improve dynamic control performance, most existing decoupling control studies were developed under low-altitude conditions and do not explicitly account for reduced gas supply capacity at low ambient pressure. Future work should therefore incorporate altitude-dependent compressor maps, cathode pressure constraints, and oxygen excess ratio limits into decoupling control design.



(**a**) (**b**)

Figure 7: (**a**) Distributed training framework of PEMFC intelligent controller based on the CIED-MD3; (**b**) Simulation results of PEMFC under random load conditions. Reprinted with permission from reference [64]. 2021, Jiawen Li; Tao Yu.

Table 2 summarizes the main air-supply control strategies discussed above. PID-based methods remain attractive for engineering applications because of their simple structure and low implementation cost, but they may not be sufficiently robust when altitude changes rapidly or the compressor approaches its operating limits. SMC improves robustness against parameter uncertainty and nonlinear air-path dynamics, although chattering and practical implementation remain concerns. MPC is more suitable for high-altitude PEMFC systems where cathode pressure, oxygen excess ratio, and compressor boundaries must be considered simultaneously. Decoupling control is also important because pressure and flow are strongly coupled in the cathode air path; however, its reliability under plateau conditions depends on accurate altitude-dependent compressor maps and system models. Overall, control development should move beyond single-variable OER regulation toward coordinated pressure-flow management under altitude-dependent constraints.

However, the above strategies are primarily established under plain conditions without considering the impact of low ambient pressure on air supply capability at high altitudes. Nonetheless, they may provide useful reference for future development of altitude-adaptive control strategies.

4.2 Energy Management and Net Power Optimization

In high-altitude PEMFC systems, maintaining stack output by increasing cathode pressure and air flow inevitably raises compressor power consumption. Therefore, improving net system power requires not only stable oxygen supply control, but also effective energy recovery and operating-point optimization. This

subsection reviews energy recovery technologies and net power optimization strategies aimed at reducing parasitic losses and improving system efficiency under high-altitude conditions.

Table 2: Comparison of representative air supply control strategies for high-altitude PEMFC systems.

Control Strategy	Main Advantage	Limitation	Relevance to High-Altitude Proton Exchange Membrane Fuel Cell (PEMFC)
Proportional-Integral-Derivative (PID)/Fuzzy Proportional-Integral-Derivative	Simple and easy to implement	Limited robustness under strong altitude variation	Suitable for basic OER regulation
Sliding Mode Control (SMC)	Robust to parameter uncertainty	Chattering and implementation complexity	Useful for nonlinear air supply dynamics
Model Predictive Control (MPC)	Handles constraints explicitly	Model accuracy and computation cost	Suitable for compressor limits and altitude-adaptive control
Decoupling Control	Separates pressure and flow control	Needs altitude-dependent compressor maps	Important for pressure-flow coordination

4.2.1 Energy Recovery Technologies

To further reduce compressor parasitic power consumption and improve PEMFC system efficiency in plateau environments, turbo-compressors have become an important development direction. In this structure, a centrifugal compressor and an expansion turbine are integrated on the same shaft. The high-temperature, high-pressure exhaust gas discharged from the stack drives the turbine, directly providing auxiliary torque to the compressor and thereby reducing the electric power consumption of the compressor motor. Sun et al. compared the performance of single-stage centrifugal compressors, two-stage centrifugal compressors, and turbo-compressors with energy recovery through thermodynamic modeling. The results showed that at a high current density of 2.0 $A{\cdot}cm^{-2}$, the exergy efficiency of the turbo-compressor system with energy recovery was 3.97% and 4.34% higher than those of the single-stage and two-stage compressor systems, respectively, while parasitic power was reduced by about 10~11 kW [48]. Ma et al. further validated the application benefits of turbo-compressors under high-altitude environments through experiments and simulations. Over the altitude range of 0–3000 m, compressor power increased from 18.1 kW to 24.9 kW and system efficiency decreased from 44.8% to 42.5%. After applying an expander, compressor power dropped to 16.8 kW and system efficiency recovered to 45.1%, significantly alleviating the performance degradation caused by plateau environments [65]. This study clearly pointed out that the operating boundary of the compressor is the key factor limiting its high-altitude operation, while the energy recovery benefit of the expander is more prominent under high-load and low-pressure conditions. Beyond hardware optimization, control-oriented energy management is another key approach to reducing parasitic power loss and improving system efficiency.

Gao et al. used an asynchronous advantage actor-critic (A3C) deep reinforcement learning algorithm for coordinated control of the air compressor and back pressure valve in high-altitude PEMFC systems. Results showed a 40% faster dynamic response and 5.8% higher electrical efficiency across three high-altitude conditions, validating intelligent energy management strategies for plateau environments [66].

Fig. 8 presents the A3C-based control framework for coordinating the air compressor and back pressure valve. By treating the PEMFC system and altitude-dependent operating conditions as the control environ-

ment, this framework aims to improve dynamic oxygen supply while reducing unnecessary compressor power consumption.

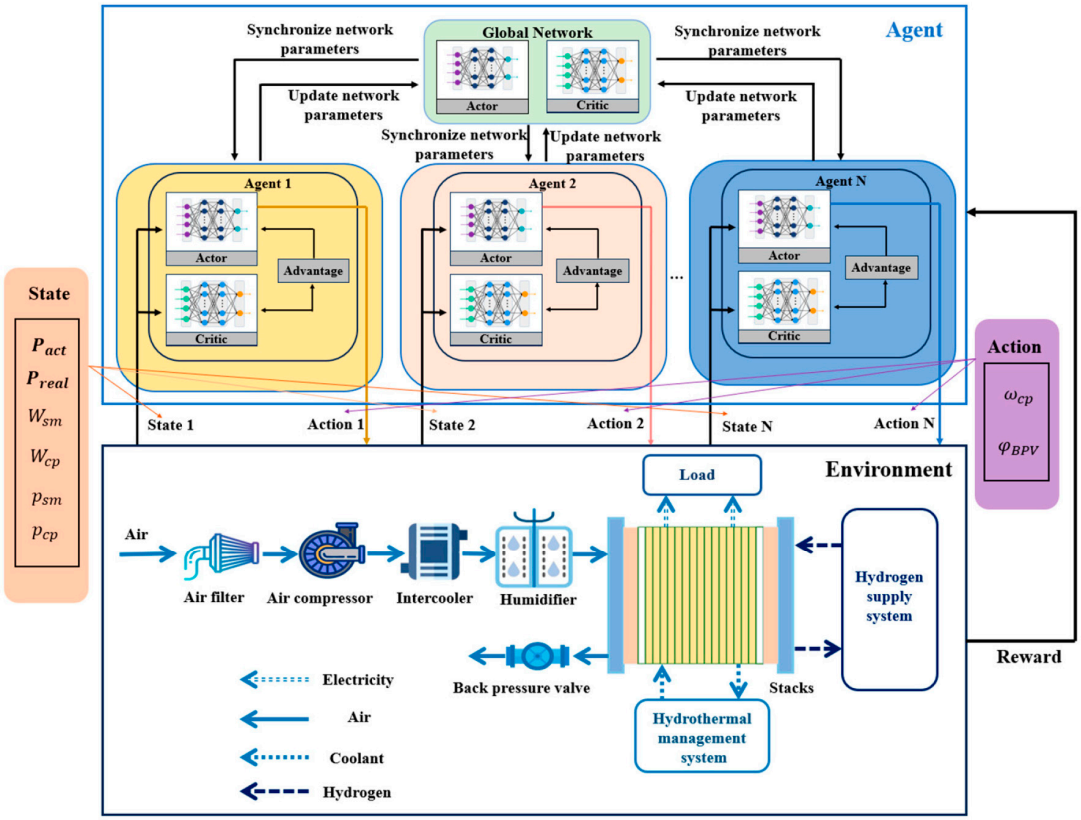


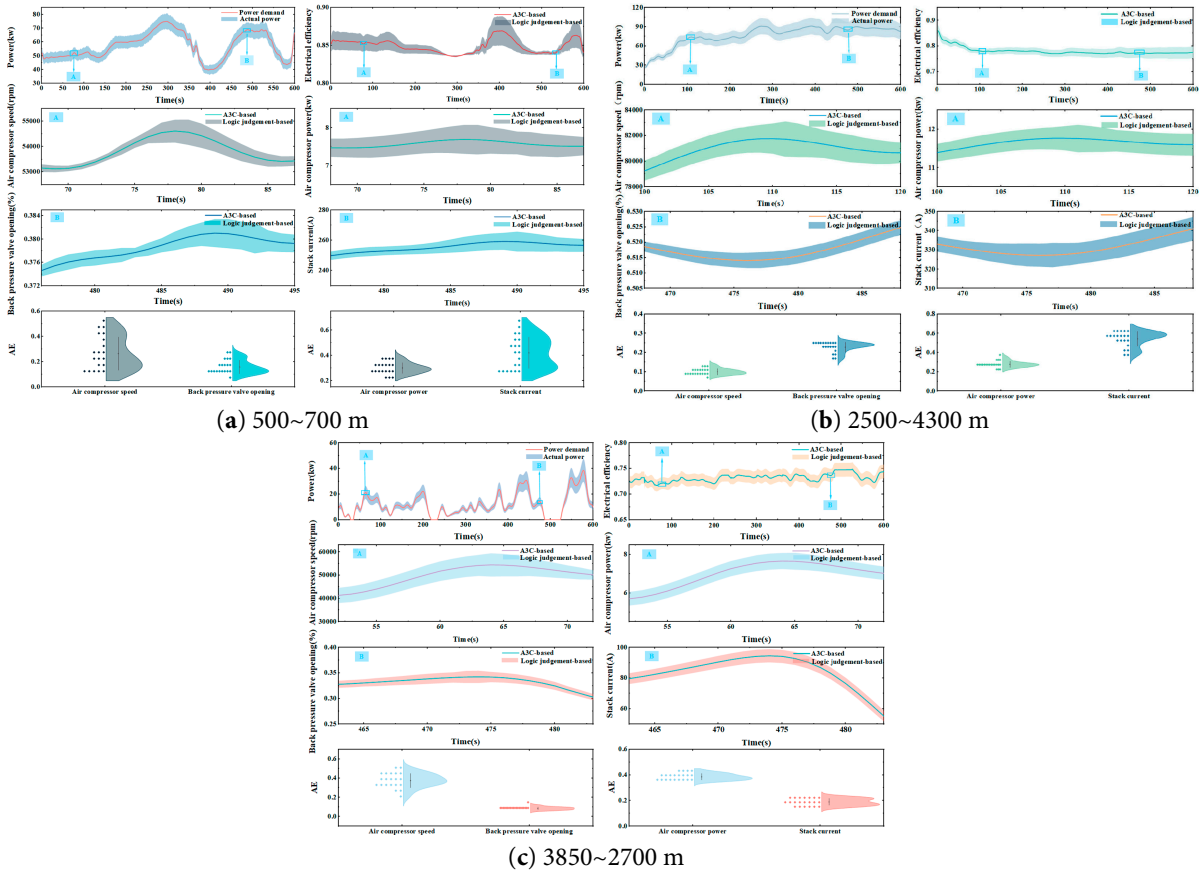
Figure 8: Intelligent control of PEMFCs air compressor and back pressure valve based on A3C. Reprinted with permission from reference [66]. 2025, Lei Gao; Xuechao Wang.

Fig. 9 further shows the system-state and efficiency responses of the A3C controller under different altitude-changing conditions. These results indicate that intelligent coordinated control can maintain more stable system operation across variable-altitude profiles, supporting its potential use in plateau PEMFC energy management.

4.2.2 Net Power Optimization Strategies

In terms of net power optimization, researchers have improved system net power and stable operation by establishing PEMFC system models for high-altitude environments and combining intelligent optimization algorithms with control strategies. Li et al. established a PEMFC power generation system model for high-altitude environments and proposed a net power optimization method based on extremum seeking and model-free adaptive control. By optimizing OER online, the method improved output power and operational stability at different altitudes while effectively avoiding compressor surge [67]. Xie et al. proposed a net power enhancement strategy that combines variable-altitude OER trajectory optimization with sliding mode control to improve system net power, and the effectiveness of this strategy under varying altitude conditions was verified on an RT-LAB semi-physical platform [68]. Chen et al. proposed a real-time power optimization strategy based on particle swarm optimization feedforward and perturbation and observation. Under altitude variations from 0 to 3000 m, the average adjustment time was only 1.8 s, and at 3000 m under

high load the power drop was only 9.1% [69]. Xie et al. further proposed a performance guaranteed control strategy (PGCS), which establishes a variable-altitude system model, analyzes and integrates system safe operation constraints, and adopts an optimization method based on partial derivatives of coupled variables to search for the optimal net power trajectory. Hardware-in-the-loop experiments showed that PGCS can significantly improve system net power by about 6.4% [70]. In intelligent optimization and system-level management, Cho et al. developed an artificial neural network (ANN) model and integrated it with MPC to provide optimal operating conditions for PEMFC systems under various load conditions. Compared with fixed set-point strategies, ANN-based MPC improved optimized system power by an average of 10.9% [71].



(**a**) 500~700 m (**b**) 2500~4300 m

(**c**) 3850~2700 m

Figure 9: System-state and efficiency responses of the A3C controller under three altitude-changing conditions: (**a**) 500–700 m, (**b**) 2500–4300 m, and (**c**) 3850–2700 m. Reprinted with permission from reference [66]. 2025, Lei Gao; Xuechao Wang.

In summary, through the synergistic effect of energy recovery technologies and intelligent optimization management strategies, the parasitic power consumption of PEMFC systems in plateau environments can be effectively reduced, and system net output power and operating efficiency can be significantly improved. This provides important technical support for the application of fuel cell systems in high-altitude environments.

5 Challenges and Future Perspectives

Although considerable progress has been made in PEMFC materials, air supply systems, and control strategies, reliable operation in high-altitude environments still faces several unresolved challenges. These

challenges mainly arise from the coupled effects of low pressure, reduced oxygen availability, low temperature, low humidity, and variable load demand. Future research should therefore move beyond isolated material or component studies and place greater emphasis on integrated stack-system behaviour under realistic high-altitude operating conditions.

5.1 Coupled Degradation under Low-Pressure, Low-Temperature, and Low-Humidity Conditions

Most existing studies on PEMFC degradation have been conducted under normal-pressure or low-altitude conditions. However, high-altitude operation involves simultaneous changes in pressure, oxygen partial pressure, humidity, and temperature. These factors may jointly affect ORR kinetics, membrane hydration, catalyst-layer water distribution, and membrane electrode durability. At present, the dominant degradation pathways of catalysts, membranes, and catalyst layers under coupled high-altitude conditions remain insufficiently understood. Accelerated aging protocols that combine low pressure, low temperature, and low humidity are therefore needed to clarify whether high-altitude operation simply accelerates conventional degradation processes or introduces additional failure modes. Such studies would provide a more reliable basis for material selection and membrane electrode design under plateau operating conditions.

5.2 Bipolar Plate and Flow-Field Design for Thin-Air Transport

Bipolar plate flow-field design has been widely studied under conventional operating conditions, but its high-altitude adaptability remains unclear. In thin-air environments, reduced gas density and oxygen partial pressure can weaken convective transport, alter pressure-drop characteristics, and narrow the water management window. Key design parameters, including rib-to-channel ratio, channel depth, channel width, and flow-field topology, may need to be reconsidered for high-altitude operation. More systematic studies are required to clarify how these geometric parameters affect oxygen transport, water removal, and pressure loss under low-pressure conditions.

5.3 Air Supply Subsystem and Compressor Operating Limits

The cathode air supply subsystem is one of the most important bottlenecks for high-altitude PEMFC systems. As altitude increases, the compressor must provide a higher pressure ratio and often operate at higher rotational speed to maintain the required cathode pressure and oxygen mass flow. This increases parasitic power consumption and may push the compressor closer to surge or overspeed limits. Although two-stage compression and turbine-assisted energy recovery have shown potential, their practical benefits depend strongly on system load, altitude, compressor efficiency, and integration strategy. Future studies should focus on the matching relationship among stack oxygen demand, compressor operating maps, pressure regulation, and net system power.

5.4 Control Robustness under Realistic Altitude Variation

Control strategies such as oxygen excess ratio control, pressure-flow decoupling, model predictive control, and net power optimization have been shown to improve PEMFC system performance. However, many of these strategies are developed under simplified or low-altitude conditions. In real high-altitude operation, ambient pressure, temperature, humidity, load demand, and compressor constraints vary simultaneously. This can lead to delayed air supply response, transient oxygen starvation, and unstable compressor operation. Therefore, future control strategies should be validated under realistic altitude transients and should explicitly consider compressor limits, water management, and system safety constraints.

5.5 Integrated Stack-System Testing and Predictive Modelling

A major limitation in current research is the lack of integrated experimental platforms that can reproduce high-altitude conditions while monitoring stack, compressor, water management, and net power behavior simultaneously. Most available studies focus either on stack performance or on system-level modelling, with limited direct connection between the two. High-altitude stack-system testing platforms that couple pressure, temperature, humidity, and dynamic load are therefore needed. The resulting data would support predictive models linking material properties, stack performance, compressor characteristics, and control parameters. Such models could help define altitude-adaptive operating windows and provide a stronger basis for PEMFC system design under plateau conditions.

6 Conclusions

This review summarized the degradation mechanisms and mitigation strategies of PEMFC systems operating in high-altitude environments. The main performance loss arises from reduced cathode oxygen availability, which increases activation and concentration polarization losses, and from the increased burden on the cathode air supply subsystem caused by lower inlet air density. Therefore, high-altitude PEMFC degradation should be understood as a coupled stack-system issue rather than a purely electrochemical problem. Existing studies indicate that catalyst-layer optimization, membrane water management, bipolar plate flow-field design, advanced compressor technologies, turbine-assisted energy recovery, and oxygen supply control can all improve high-altitude adaptability. Overall, reliable PEMFC operation in plateau and other high-altitude regions depends on coordinated optimization of stack materials, component design, air supply hardware, and system control.

Acknowledgement: Not applicable.

Funding Statement: The authors received funding from Doctoral research funding of Hubei University of Technology (XJ2024008201) and Open funding of Hubei Engineering Research Center for Safety Monitoring of New Energy and Power Grid Equipment for this study (HBSEES202515).

Author Contributions: The authors confirm contribution to the paper as follows: Conceptualization, Jianxin Pan and Xinghe Fan; writing-review and editing, Writing-original draft, Yimeng Chen, Huachen Du and Zhiming Feng; visualization and supervision, Xiaoxing Zhang; All authors reviewed and approved the final version of the manuscript.

Availability of Data and Materials: Not applicable.

Ethics Approval: Not applicable.

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

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