Development of PEMFC Applications in Transportation

Junyi Wu*

College of New Energy and Materials, China University of Petroleum (Beijing), Beijing 102249, China

Abstract. As a promising power technology for low-carbon transportation, proton exchange membrane fuel cells (PEMFCs) have garnered increasing attention owing to their high energy conversion efficiency, zero emissions, and rapid refueling capabilities. However, the large-scale deployment of PEMFCs in transportation systems is still constrained by high manufacturing costs, insufficient durability, and an underdeveloped hydrogen infrastructure. This review systematically summarizes the latest research progress of PEMFC applications in land, maritime, and aerospace transportation sectors. Special emphasis is placed on the performance improvement requirements under different operating scenarios and the corresponding technical strategies, including catalyst interface engineering, system-level optimization, corrosion resistance design for marine environments, and lightweight structural design for aviation applications. The current technical and economic challenges hindering the commercialization of PEMFCs are analyzed in depth, and the future development trends are discussed from the perspectives of material innovation, system integration, and industrial ecosystem coordination. This work highlights the significance of scenario-driven design and interdisciplinary collaboration in advancing PEMFC technology.

1 Introduction

Driven by the global energy transition and the goal of carbon neutrality, hydrogen energy, as a clean and efficient secondary energy source, has increasingly prominent strategic value in the transportation sector. Proton exchange membrane fuel cells (PEMFCs) can efficiently and directly convert hydrogen energy into electrical energy, and possess the advantages of zero emissions, low noise, and rapid start-up, making them an important research direction for the power systems of various transportation vehicles. Nevertheless, their large-scale commercialization is still restricted by factors such as high costs, insufficient durability, and the underdevelopment of hydrogen energy infrastructure.

In recent years, a series of breakthroughs in the field of materials science, such as the development of low-platinum/non-noble metal catalysts (e.g., Pt/oxide, Fe/N-C catalysts) and lightweight high-performance bipolar plates, have provided key support for improving the core performance of PEMFCs and reducing system costs [1-3]. For instance, the CoO_x

---

* Corresponding author: 2023011382@student.cup.edu.cn

@Pt/C cathode catalyst developed by Peng et al. exhibits significantly improved activity and durability compared with the currently widely used Pt/C catalysts; the composite bipolar plate researched by Chen et al. adopts a ternary composite system of natural graphite/expanded graphite/carbon nanotubes. Through the design of a double percolation structure, it significantly improves the mechanical strength while maintaining high electrical conductivity, and achieves an ultra-thin structure with a thickness of less than 0.6 mm, which strongly promotes the improvement of the overall energy density and cost control of the PEMFC system [4].

This paper aims to systematically review the current status of PEMFC applications in the transportation sector, deeply analyze the core strategies of material innovation and system integration optimization, comprehensively discuss the current technical and economic challenges, and put forward prospects for the commercialization path of hydrogen energy transportation in the future.

2 Application status of PEMFCs in the transportation sector

2.1 Passenger vehicle sector

In the passenger vehicle sector, PEMFC sedans have gradually entered the initial stage of demonstration and commercialization. The current mainstream models in the market include Toyota Mirai, Honda Clarity FCV, and Hyundai NEXO. The global sales volume in 2023 was approximately 10,000 units, accounting for less than 0.1% of total automobile sales. In China, enterprises represented by SAIC Motor, Changan Automobile and GAC Group are actively participating in the demonstration operation under the policy of the "Fuel Cell Vehicle Demonstration City Cluster". At present, these vehicles are mainly used in scenarios such as online car-hailing and official business vehicles. The power of the current passenger vehicle fuel cell system is generally in the range of 80–120 kW, with a cruising range of up to 600–800 km and a hydrogen refueling time of about 3–5 minutes, which has obvious advantages over pure electric vehicles in terms of driving range and energy supplement efficiency.

2.2 Commercial vehicle sector

The application progress of PEMFCs in the commercial vehicle sector such as heavy-duty trucks, buses and special-purpose vehicles is more remarkable. Internationally, Hyundai XCIENT hydrogen fuel cell heavy-duty trucks have been mass-deployed in the European market; Toyota has also launched commercial models based on the Mirai system. In the Chinese market, enterprises such as Dongfeng Motor, SAIC Motor and FAW Group have launched a variety of PEMFC heavy-duty trucks. The system power of these heavy-duty trucks is generally between 120 and 200 kW (usually achieved through the combination of double-stack or triple-stack modules), with a maximum cruising range of more than 800 km. In 2023, the global sales of PEMFC heavy-duty trucks were about 10,000 units, with the Chinese market accounting for more than 50%, mainly applied in high-frequency and high-load scenarios such as port container transportation, mining short-haul transportation, intercity trunk logistics and urban muck removal. In addition, fuel cell buses have carried out large-scale demonstration operations in the public transport systems of Beijing, Shanghai, Zhangjiakou and other cities.

2.3 Maritime sector

In marine power systems, PEMFCs can be used as the main propulsion power or auxiliary power system, which significantly reduces the emissions of sulfur oxides, nitrogen oxides and particulate matter, complying with the increasingly stringent environmental protection regulations of the International Maritime Organization (IMO). At present, the applications of PEMFCs in ships are mainly concentrated in scenarios such as inland river short-distance passenger ships, port operation ships, ferries and scientific research ships, and are in the initial stage of commercialization. Demonstration projects such as the European fuel cell ferry "FELIX" and China's "Three Gorges Hydrogen Vessel 1" have realized commercial trial operation. In terms of technical routes, marine PEMFC systems need to have high power output (hundreds of kilowatts to megawatts) as well as good anti-vibration and corrosion resistance performance. Furthermore, to effectively cope with the variable load conditions of ships, the system often needs to be combined with lithium batteries to form a hybrid power system. However, the maritime sector still faces challenges such as limited hydrogen storage space, lack of hydrogen refueling infrastructure, insufficient verification of system durability and safety, especially ocean-going ships put forward higher requirements for system reliability and service life.

2.4 Aerospace sector

In the aerospace sector, PEMFCs are currently mainly used in scenarios such as unmanned aerial vehicles (UAVs), small electric aircraft, satellite auxiliary power supplies and manned space life support systems. For UAVs, PEMFCs can significantly extend the endurance time, suitable for long-time monitoring, logistics distribution and emergency communication tasks, with a power demand of 200 W-1 kW. For example, the "ScanEagle" fuel cell UAV developed by Boeing in the United States has achieved continuous flight for more than 12 hours. In the field of manned aircraft, enterprises such as Airbus and ZeroAvia are actively promoting the research and development of hydrogen fuel cell regional aircraft with the goal of realizing zero-emission commercial flight by 2035. The power demand of PEMFCs on airliners is 200 kW to several megawatts. In addition, in the aerospace field, PEMFCs can be used as backup power supplies for re-entry capsules, space stations or lunar bases, and supplement energy for life support systems. More importantly, the water by-product generated by its reaction can be used for astronauts' drinking or oxygen regeneration, thus realizing the recycling of resources. However, aerospace applications put forward extremely high requirements for the power-to-weight ratio, low-temperature start-up performance, system reliability and safety standards of PEMFCs. At present, the relevant technologies are still in the stage of verification and prototype development, and have not yet formed large-scale applications.

3 Performance improvement requirements and technical countermeasures

3.1 Performance improvement and technical countermeasures of automotive PEMFCs

3.1.1 Catalyst optimization

The traditional research idea focuses on reducing platinum (Pt) loading or developing non-noble metal alternatives, while the CoO_x@Pt/C catalyst proposed by Peng et al. represents a more refined "interface engineering" strategy [1]. Its innovation lies in the precise embedding of sparse cobalt oxide (CoO_x) clusters into sub-2 nm Pt nanoparticles. It regulates the electronic structure of Pt through the strong metal-support interaction, and anchors Pt nanoparticles by oxide clusters, which simultaneously inhibits their Ostwald ripening and agglomeration in the electrochemical environment from both physical and chemical aspects. Studies have shown that the mass activity of CoO_x@Pt/C is significantly superior to that of commercial Pt/C and PtCo/C catalysts, and it exhibits more excellent performance in terms of power density, Pt utilization rate and long-term stability. After a large number of cyclic accelerated stress tests, its mass activity can still be maintained at a high level, with a longer service life, and much lower voltage loss than the comparison samples, showing prominent stability advantages. This case indicates that compared with simply reducing the amount of Pt, the fine regulation based on interface engineering can achieve the synergistic improvement of activity and durability, which is more in line with the actual demand of automotive PEMFCs for "long service life + high load".

However, the synthesis process of this strategy is relatively complex, with extremely high requirements for the size, distribution of cobalt oxide clusters and the interface control with Pt, and the large-scale production cost and consistency are facing challenges. In addition, its long-term stability still needs to be further verified in real on-vehicle working conditions that may contain impurities (such as CO and SO_2 poisoning).

3.1.2 Low-temperature adaptation and rapid start-up

The adoption of a two-stage current ramp loading strategy can effectively improve the cold start speed and energy efficiency [5]. This strategy divides the start-up process into two stages through a one-dimensional multi-physics model: the first stage adopts a high-slope current to achieve rapid temperature rise, and the second stage adopts a low-slope current to suppress the risk of icing. Combined with artificial neural network and genetic algorithm to optimize parameters, the optimal loading strategy is obtained. Experiments show that compared with traditional methods, this strategy shortens the start-up time by 64%, with the lowest energy consumption per unit temperature rise and the highest effective heat production efficiency. This case shows that compared with the traditional scheme relying on hardware redundancy or external heating, the control strategy based on model prediction and intelligent optimization can achieve a significant improvement in cold start performance at a lower system cost, providing a "software-driven" improvement path for the application of PEMFCs in transportation in cold regions.

Nevertheless, the optimization effect of this strategy is highly dependent on the accuracy of the model. Factors such as the attenuation of the actual stack and the uneven hydrothermal state may cause model mismatch and affect the control effect. In addition, embedding complex optimization algorithms into automotive-grade controllers puts forward higher requirements for chip computing power and real-time performance, which also increases the complexity and cost of the system.

3.1.3 Air circulation system

The air circulation system is also a key factor affecting the efficiency and stability of fuel cells. A study by Santiago Martinez-Boggio et al. compared three air path layouts: electric compressor system (e-Compressor), coupled electric auxiliary turbocharging system (e-Turbocharging Coupled), and decoupled electric auxiliary turbocharging system (e-Turbocharging Decoupled). The team employed the non-dominated sorting genetic algorithm III (NSGA-III) and Design of Experiments (DoE) method, constructed a fuel cell system model on the GT-Suite platform, and carried out simulation optimization under multiple working conditions. It was found that the coupled electric auxiliary turbocharging system can increase the system output power by about 10% under high current load, and reduce the peak power demand of the motor by about 60%, which is the optimal architecture that can significantly improve the output power and reduce the motor size [6].

At the same time, the study shows that the optimization of the air circulation system should not only focus on the efficiency of a single component, but also need to balance the coupling relationship among output power, parasitic power and motor size from the system level. Through energy path integration, the coupled e-Turbo architecture shows better comprehensive performance under high load conditions, and is especially suitable for automotive PEMFC scenarios with frequent high-power operation. However, its high structural integration also puts forward higher requirements for control strategies and system reliability.

3.2 Performance improvement and technical countermeasures of marine PEMFCs

3.2.1 Hydrogen storage optimization

Hydrogen storage by adsorption using metal-organic frameworks (MOFs) is a technical path suitable for marine scenarios [7]. MOFs materials have a high specific surface area and adjustable pore structure, and can achieve high-density hydrogen storage at low temperature and low pressure. For example, the hydrogen storage density of MOF-5 can reach 8.24 wt% under the conditions of 77 K and 3.5 MPa, which is higher than the currently commonly used high-pressure gaseous hydrogen storage system for ships. Materials such as ZIF-8 and UIO-66 have a slightly lower hydrogen storage density but better hydrothermal stability, which is more adaptable to the marine environment. Grand canonical Monte Carlo (GCMC) simulation and experiments show that MOFs materials exhibit good stability in cycles and have engineering application potential. However, their practical application still faces challenges such as high cost, complex forming process and poor thermal conductivity (affecting the speed of hydrogen charge and discharge). This indicates that MOFs hydrogen storage is more suitable for marine application scenarios with limited space and low energy supplement frequency, rather than ocean-going ships with extremely high requirements for rapid hydrogen charge and discharge.

3.2.2 System thermal management

Integrating a honeycomb heat exchange device in the hydrogen storage tank can effectively suppress temperature fluctuations, reduce the temperature rise during hydrogen charge/discharge processes by 5.6%–16.1%, and increase the system available capacity ratio by about 4.4%. This optimization is especially suitable for materials with high hydrogen storage performance but poor thermal conductivity such as MOF-5, which helps to realize the stable operation of the hydrogen storage system. In the future, the system energy efficiency can be further improved through waste heat recovery and hybrid integration with PEMFC/lithium batteries.

Although the method of integrating honeycomb heat exchange devices can alleviate the thermal conductivity problem, it also increases the complexity of the system, and its long-term cycle stability and performance attenuation in real marine vibration and tilt environments are still unknown.

3.2.3 Anti-salt and alkali corrosion measures

A review by Li et al. systematically constructed a full-chain, multi-component collaborative defense system for the marine salt spray environment [8], rather than discussing the protection of a single component in isolation. This system innovatively covers a complete protection path from air inlet filtration (salt spray filter), to surface modification of core components (bipolar plate coating, GDL hydrophobic treatment), and then to material bulk optimization (chlorine-resistant catalysts, pollution-resistant membranes). This systematic idea clarifies the multi-layer defense mechanism of "blocking-tolerance-recovery", and provides a comprehensive technical menu for the system design of marine PEMFCs.

However, at present, many protective measures (such as special coatings and modified membranes) are still in the laboratory stage, and their long-term protective effects, large-scale preparation processes and additional costs have not been verified through practice. In addition, the superposition of multi-layer protection may introduce new interface problems or reduce the system power density, and the regular flushing scheme increases the complexity of operation and maintenance and fresh water consumption, so the final technical scheme needs to be analyzed in combination with actual conditions.

3.3 Performance improvement and technical countermeasures of aerospace PEMFCs

3.3.1 Environmental adaptability

Low-pressure environment is the main factor leading to the decline of PEMFC performance at high altitude. Differentiated strategies can be adopted for different flight missions: for ordinary airliners, increasing the intake humidity can significantly improve the power output. For example, increasing the humidity from 20% to more than 50% during the cruise phase at 11,000 m can increase the system power from 53.72% to 70.88%; for high-power demand missions (such as long-endurance UAVs), a supercharging system needs to be adopted to maintain high power output, although it will increase the system complexity and cost [9]. Notably, for aerospace PEMFCs without external humidification, Zhang et al. clarified the key effects of temperature, cathode pressure and stoichiometric ratio through experiments: low-pressure environment will cause uneven oxygen transmission and distribution, while the high air flow rate commonly used at high altitude will aggravate membrane dehydration, leading to performance degradation and voltage fluctuation [10]. To this end, they constructed a high-precision "1+1 dimensional" stack model to accurately predict working conditions, and then proposed a set of phased adaptive optimal control strategies. This strategy adjusts the operating parameters in real time according to the flight profile, and the actual measurement shows that the stack voltage consistency is significantly improved—the voltage fluctuation range is reduced by 50% (from 120 mV to 60 mV), and the average output voltage is increased. This indicates that the intelligent control strategy based on model prediction and environmental perception can systematically address the challenge of ensuring stable operation of aerospace PEMFCs under wide-ranging dynamic operating conditions, and realize a leap from component optimization to system coordination.

Both humidification and supercharging schemes will increase the system complexity, weight and parasitic power, which is contrary to the fundamental demand of aircraft lightweight. Therefore, how to design an efficient and lightweight environmental control subsystem is the core challenge to balance performance and weight.

3.3.2 Lightweight and high power-to-weight ratio improvement

The mass of bipolar plates accounts for about 80% of the total mass of PEMFCs, and their lightweight is the key to system weight reduction. Recent research on the lightweight of bipolar plates shows the characteristics of parallel development and in-depth trade-off of multiple technical paths [2, 11]. The innovation lies not only in the breakthrough of a single technology, but also in the precise matching of the most suitable process combination according to the needs of aerospace missions. The coated ultra-thin metal plate process is relatively mature and has been used in demonstration stacks; carbon-based composite materials have prominent comprehensive advantages in lightweight and corrosion resistance; additive manufacturing integrated design provides the possibility for core-frame integration and complex flow channel customization, which is suitable for small-batch aerospace stacks. This indicates that there is no optimal method in the aerospace field, but precise matching based on application scenarios is needed. Table 1 summarizes the weight reduction effect and aerospace applicability of bipolar plates with different processes.

Table 1. Weight reduction effect of bipolar plates with different processes.

Materials/Processes	Weight Reduction Effect	Aerospace Applicability
Coated ultra-thin metal plate	30–50% weight reduction	High, has been used in aerospace demonstration stacks
Carbon-based composite material	40–60% weight reduction	High, especially suitable for lightweight and corrosion resistance requirements
Additively manufactured integrated design	Reduction in the number of assembled parts, 10–20% overall weight reduction	Medium-high, suitable for customized and small-batch aerospace stacks
Surface coating/treatment	Almost no weight gain, extended service life	High, improves durability without affecting weight

However, these methods also have their own disadvantages. The stamping process and corrosion-resistant coating of ultra-thin metal plates are facing challenges, which are prone to deformation and the long-term reliability of the coating is questionable. The electrical conductivity, air tightness and bonding strength with the resin matrix are the key bottlenecks of carbon-based composite materials. Additive manufacturing is limited by material electrical conductivity, printing precision and efficiency, and the current cost is extremely high. All weight reduction processes must be on the premise of not sacrificing electrical conductivity, mechanical strength and durability, which constitutes a huge technical challenge. This case further shows that the performance improvement of aerospace PEMFCs does not rely on a single material breakthrough, but more on the system-level design and manufacturing process collaborative optimization around mission requirements.

4 Challenges and development

Overall, the commercialization of PEMFCs in transportation is at a critical juncture, requiring breakthroughs in multiple bottlenecks to achieve large-scale deployment. The core challenges are still multiple obstacles lying ahead of large-scale application. First, the structural contradictions of the industrial chain are prominent. The large-scale, low-cost preparation and efficient storage and transportation system of upstream green hydrogen energy are not yet perfect, and the construction of hydrogen refueling infrastructure network is lagging behind, resulting in high hydrogen energy supply cost and insufficient stability, which seriously restricts the promotion of downstream vehicles and ships. Second, the independence and maturity of key technologies need to be improved. Core materials and components such as high-performance proton exchange membranes, low-platinum/non-platinum catalysts and high-reliability air compressors have not yet completely got rid of the dependence on imports, posing risks to supply chain security. In addition, the engineering verification and long-term durability data of some laboratory technologies (such as special anti-corrosion coatings and new hydrogen storage materials) are scarce. Finally, a sustainable business model has not yet been formed. The high initial purchase cost, imperfect infrastructure and high hydrogen use cost lead to insufficient economic efficiency of terminal applications. The industry as a whole is still highly dependent on government subsidies and demonstration projects, and has not yet formed a market-oriented cycle with endogenous power.

The future development path needs to focus on systematic breakthroughs and ecological construction. At the technical level, we must adhere to the independent innovation and process iteration of core materials, accelerate the transformation of laboratory achievements into engineering and productization through the deep integration of industry, university and research, focus on overcoming technical problems of long service life, low cost and high environmental adaptability (such as marine anti-salt and alkali corrosion, aerospace ultra-lightweight), and optimize system control and energy efficiency management by using intelligent and digital means. At the industrial level, it is necessary to strengthen the collaborative layout of the whole industrial chain, and orderly promote the network construction of green hydrogen preparation, storage and transportation and refueling infrastructure through the combination of policy guidance and market mechanisms to support the expansion of application scale. At the commercial level, we should actively explore diversified business models, such as financial leasing, energy contract management, and hydrogen-electric integrated operation, and continuously reduce costs through economies of scale, gradually decreasing reliance on financial subsidies, and finally build a green hydrogen energy transportation ecosystem with independent and controllable core technologies, complete industrial chain and self-consistent business logic.

5 Conclusions

This paper has systematically reviewed the application status and technical progress of PEMFCs in land, maritime, and aerospace transportation. Studies show that this technology has taken the lead in realizing demonstration applications in scenarios such as commercial vehicles, highlighting the advantages of long cruising range, rapid refueling and zero emissions; however, its large-scale commercialization is still restricted by core bottlenecks such as cost, durability and hydrogen energy infrastructure. In view of the stringent requirements of different scenarios of vehicles, ships and aerospace, this paper analyzes the adaptive material innovation and system optimization strategies such as high-stability catalysts, corrosion-resistant engineering and lightweight design, and points out that the core of the technology lies in breaking the traditional trade-off relationship among performance, cost and environmental adaptability.

This review clarifies the technical differences and common challenges of the cross-field application of PEMFCs, not only sorts out the key research directions from material innovation to system integration for the academic community, but also provides decision-making basis for the industrial community to identify technical breakthroughs and plan research and development paths. In the future, the technological development of PEMFCs will focus on "scenario-driven" and "whole-chain collaboration": the research and development of materials and systems need to closely focus on the extreme needs of each scenario, such as marine corrosion resistance and aerospace ultra-lightweight; at the same time, through the simultaneous advancement of core technology breakthroughs, infrastructure improvement and business model innovation, its commercialization process will be accelerated, laying a solid technical foundation for the deep decarbonization of the transportation sector.

References

1. B. Peng, Z. Liu, L. Sementa et al., Embedded oxide clusters stabilize sub-2 nm Pt nanoparticles for highly durable fuel cells. Nat. Catal. **7**, 123–134 (2024).
2. E.F. Hidayat, Juliandri, S.M. Zain, A.R. Noviyanti, Advances in proton exchange membrane fuel cell (PEMFC) materials: A review of developments from 2021 to 2025. J. Power Sources **628**, 238124 (2025).
3. Y.S. Zhao, J.W. Wan, C. Ling, et al., Acidic oxygen reduction by single-atom Fe catalysts on curved supports. Nature **631**, 456–462 (2025).
4. J. Chen, R. Fan, N. Qin, Recent advances on materials and technologies of composite bipolar plate for proton exchange membrane fuel cell. J. Power Sources **594**, 234009 (2023).
5. Y.J. Chen, W.Z. Fang, G.R. Zhao, et al., Optimizing current loading strategies for PEMFC stacks and predictions of needed powers for successful cold starts. Appl. Therm. Eng. **250**, 129479 (2025).
6. S. Martinez-Boggio, D. Di Blasio, T. Fletcher, R. Burke, A. García, J. Monsalve-Serrano, Optimization of the air loop system in a hydrogen fuel cell for vehicle application. Energy Convers. Manag. **283**, 116911 (2023).
7. M. Wu, Q. Zheng, Evaluation of storage performance of hydrogen adsorption on typical kinds of MOFs for ship's PEMFC power units: By GCMC, numerical simulations and experiments. J. Energy Storage **106**, 114889 (2025).
8. S. Li, J.K. Zhu, G. Yang, Q. Shen, A Review on Impact of the Marine Salt Spray Environment on the Performance of Proton Exchange Membrane Fuel Cells. J. Mar. Sci. Eng. **13**, 172 (2025).
9. L. Kang, S. Lin, S. Bao, J. Mao, Modeling and analysis of performance degradation in proton exchange membrane fuel cell system for aviation applications. Aerosp. Sci. Technol. **162**, 110236 (2025).
10. Y. Zhang, Z. Hu, L. Xu, H. Liu, K. Ye, J. Li, M. Ouyang, Fuel cell system for aviation applications: Modeling, parameter sensitivity, and control. Energy Convers. Manag. **312**, 118555 (2024).
11. Y. F. Xue, M. Alnajideen, R. Navaratne, Evolution of Proton Exchange Membrane Fuel Cell Technology for Aviation Applications: A Review. Energy Fuels **39**(8), 5678–5692 (2025).