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Study On Energy Conversion Efficiency Improvement of Hydrogen Fuel Cell Vehicles Based on Membrane Electrode Modification and Intelligent Thermal Management

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Abstract:

With the advancement of global energy transition hydrogen fuel cell vehicles are receiving more and more attention as a kind of transportation with good environmental performance. The energy conversion efficiency of hydrogen fuel cell system is a key factor in determining its economy and wide application. This study aims to improve the overall energy conversion efficiency of hydrogen fuel cell vehicles through the combination of membrane electrode modification and intelligent thermal management strategies. First, for the structural optimization of the membrane electrode of the hydrogen fuel cell, nanocatalyst and carbon-based carrier modification techniques were used to improve the activity of the catalyst and the ionic conductivity of the membrane electrode, thus enhancing the energy output and stability of the electric stack. Secondly, through active cooling and temperature feedback control strategies, the thermal effects of fuel cells under high loads and dynamic operating conditions were effectively addressed, reducing energy losses in the system. The combined results of various studies indicate that the integrated application of membrane electrode modification and intelligent thermal management significantly improves the energy conversion efficiency of hydrogen fuel cell vehicles, reduces energy consumption, and simplifies system temperature control. Finally, this study also explores the cost and engineering feasibility, and proposes the future development direction of hydrogen fuel cell vehicles in commercialization and practical applications. Through the optimization strategy of this study, the energy efficiency improvement of hydrogen fuel cell vehicles has important theoretical significance and application value.

Keywords: Hydrogen Fuel Cell; Membrane Electrode Assembly; Thermal Management; Catalyst Modification; Energy Efficiency

1. Introduction

Under the impetus of global carbon neutrality targets, the automotive industry is rapidly transitioning toward clean energy solutions. Fuel Cell Electric Vehicles (FCEVs), characterized by zero emissions, high energy density, and rapid refueling capabilities, have emerged as a key direction in the development of new energy vehicles. However, the current generation of commercial FCEVs still faces limitations in energy conversion efficiency, which constrains further improvements in driving range, system stability, and operational cost optimization.

As a critical component within the fuel cell stack, the membrane electrode assembly (MEA) plays a decisive role in determining electrochemical reactivity and overall energy output. During operation, the MEA generates significant heat loss, which adversely affects reaction efficiency. Conventional thermal management approaches often suffer from delayed response and high energy consumption, making them insufficient to meet the dual demands of thermal balance and energy efficiency under dynamic operating conditions. By modifying the catalyst layer and support structure of the MEA—such as enhancing catalyst dispersion, electrical conductivity, and corrosion resistance—the electrochemical reaction efficiency and durability can be significantly improved, thereby increasing both reactivity and service life. Furthermore, the development of adaptive thermal management systems capable of dynamic thermal regulation and energy recovery can facilitate real-time heat flow control, contributing to further enhancement of the overall system efficiency.

Significant research progress has been made in the structural modification of MEA for hydrogen fuel cells. In recent years, considerable attention has been directed toward the modification of catalysts and ion-conductive membranes. The development of non-platinum and low-platinum catalysts has been particularly prominent, aiming to enhance catalytic activity and stability while simultaneously reducing material costs. Thermal management systems have also become a focal point of research. Emerging approaches integrate heat recovery and energy feedback mechanisms, with the goal of capturing excess thermal energy and converting it into usable power, thereby improving the overall energy efficiency of the system [1].

This study focuses on enhancing the energy conversion efficiency of hydrogen fuel cell vehicles by systematically reviewing recent advances in membrane electrode modification and thermal management strategies. In terms of membrane electrodes, the research summarizes key technological pathways, including nanocatalyst functionalization, porous structure optimization, carbon-based support substitution, and ion transport regulation. It specifically analyzes the mechanisms and research outcomes of these modifications in improving catalytic activity, structural stability and conductivity. Regarding thermal management, the study reviews the structural design and control strategies of current systems, with particular emphasis on methods such as coolant flow regulation and temperature feedback control, which have demonstrated effectiveness in improving temperature field uniformity and operational stability of the fuel cell stack.The integrated optimization of MEA structure and thermal management has emerged as a critical research direction for enhancing overall system performance, showing promising prospects for practical engineering applications.

Ultimately, it is expected to provide a theoretical basis and technical support for the commercial application of hydrogen fuel cell vehicles and to promote its wide application in the field of transportation.

2. Hydrogen Fuel Cell System Structure and Energy Conversion Analysis

Hydrogen fuel cell vehicles consist of a fuel cell stack, gas supply system, cooling system, energy management system, and power output system, which work together to efficiently convert hydrogen chemical energy into mechanical energy. The stack is the core component, composed of multiple series-parallel connected single cells. Hydrogen undergoes a catalytic reaction at the anode to release electrons and protons. The electrons form a current through the external circuit, while the protons pass through the electrolyte membrane to the cathode, where they react with oxygen to produce water and heat, thereby generating electrical energy.

The gas supply system is responsible for storing and supplying high-pressure hydrogen (35–70 MPa) and compressed air in controlled quantities, and is equipped

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with circulation and humidity regulation modules to enhance supply stability and system safety. The cooling system uses a liquid cooling circuit and heat exchange units to maintain the stack temperature within the range of 60–80°C, preventing performance degradation caused by overheating. The energy management system performs real-time adjustments to operational status and temperature control parameters to ensure system stability. The power output system converts direct current into alternating current to drive the motor. Some vehicle models also integrate power batteries or supercapacitors to achieve energy recovery and peak power assistance, thereby improving overall vehicle efficiency and responsiveness [2].

The energy conversion path of fuel cells involves a multistage conversion from chemical energy to electrical energy to mechanical energy. During this process, there are activation losses, ohmic losses, concentration polarization losses, and heat losses, among which the overpotential of catalytic reactions, electrolyte membrane impedance, and uneven gas concentration distribution are the main influencing factors. In addition, failure to dissipate heat in a timely manner will also reduce stack efficiency and stability.

System performance evaluation typically uses metrics such as stack efficiency, system efficiency, and vehicle energy efficiency to comprehensively reflect its energy conversion capability and economic performance.

3. Electrode Structure Modification Study

3.1 Membrane Electrode Composition and Key Performance Parameters

MEA is the core component of hydrogen fuel cell, which is responsible for accomplishing the electrochemical reaction process between hydrogen and oxygen. It consists of three main parts: catalytic layer, proton exchange membrane and gas diffusion layer. Among them, the catalytic layer is mainly used to catalyze the electrochemical reaction between hydrogen and oxygen, the proton exchange membrane is responsible for proton conductivity and gas isolation, and the gas diffusion layer provides an effective transmission channel for hydrogen and oxygen.

Key parameters of the catalyst layer include catalyst activity, gas diffusion coefficient, electrical conductivity, and ion transport rate. The particle size and dispersion of the catalyst significantly influence its activity, which in turn determines the reaction rate and power output of the fuel cell. The gas diffusion coefficient affects the distribution of reactant gases within the catalyst layer, while electrical conductivity directly impacts the efficiency of both electron and ion transport. The ion transport rate is crucial for proton conduction between electrodes, with higher transport rates effectively reducing ohmic losses across the membrane.

As one of the most critical components of the fuel cell stack, the proton exchange membrane must exhibit excellent proton conductivity, thermal stability, and resistance to chemical degradation. Due to the poor performance of fluoropolymer membranes like Nafion under low-temperature and low-humidity conditions, recent research has shifted toward developing composite and non-fluorinated membranes with stable conductivity under high-temperature, low-humidity environments. The gas diffusion layer, on the other hand, has the role of providing a channel for uniform gas distribution and current transmission. Its porosity, electrical conductivity, and hydrophilic/hydrophobic properties have a significant impact on the performance and stability of the battery. Excessively high or low porosity affects gas transport and water management, which ultimately affects the power output and stability of the battery over a long period of operation [3].

3.2 Modification Methods and Technology Paths

3.2.1 Nanocatalyst Modification

In the study of fuel cell catalysts, platinum-based catalysts are widely used for hydrogen oxidation and oxygen reduction reactions due to their excellent catalytic activity. However, the high cost and limited resources of Pt make the economics and sustainability of the catalysts challenging. In recent years, researchers have modified Pt-based catalysts by alloying and nanosizing, aiming to improve their activity and stability while reducing the use of platinum.

Pt-M (M is transition metal such as Co, Ni, Fe, etc.) alloy catalysts are one of the more studied modified catalysts. Pt-Co alloy catalysts have been widely investigated for their higher oxygen reduction reaction activity and better stability. It has been shown that the mass activity of Pt-Co alloy at 0.9 V is four point five times higher than that of conventional Pt/C catalysts [4].

Non-precious metal catalysts such as Fe-N-C and Co-N-C catalysts have made remarkable progress in recent years. It has been shown that Fe-N-C type catalysts with high catalytic activity and low cost can replace the noble metal Pt in oxygen reduction reaction. Huang et al. reported that compared to conventional Pt catalysts, Fe–N–C catalysts exhibit stronger adhesion to Nafion ionomers at 298 K and 358 K, and their Fe_3N nanoparticles demonstrate enhanced adsorption capacity during redox reactions [5].

3.2.2 Porous Structure Optimization

The porous structure of the catalytic layer is crucial for the reaction efficiency and stability of fuel cells. The porous structure can effectively enhance gas transport and reactant supply, but excessive porosity may lead to uneven catalyst distribution and degradation of cell performance. In order to optimize the porous structure of the catalytic layer, researchers have proposed design schemes such as hierarchical porous structure and gradient pore distribution.

The catalytic layer with hierarchical porous structure consists of a variety of pore sizes, and the fine pore layer facilitates charge transport and proton conductivity, while the larger pore sizes contribute to gas diffusion and water drainage. Zhang et al. developed a Co–N–C#2 catalyst with a three-dimensional porous structure, which facilitates the formation of enhanced mass transport channels, thereby improving the electrocatalytic activity of the catalyst [6]. In addition, the catalytic layer design with gradient pore distribution makes gas diffusion and water management more efficient by adjusting the pore size in different regions. The study shows that the oxygen transport characteristics in the catalytic layer can be effectively improved by constructing the diffusion layer model under the three flow fields of parallel, serpentine and lobe, and regulating the size and distribution of porosity; among them, a reasonable increase in local porosity can improve the uniformity of the oxygen mole fraction distribution and the membrane current density, which can significantly optimize the polarization and power output, providing a theoretical basis for the optimization of the design of diffusion layer structure under different flow field conditions. This provides a theoretical basis for the design and optimization of the diffusion layer structure under different flow conditions. Through the design of gradient pore size, the catalyst can maintain the optimal gas supply and water production management during the working process of the battery, thus improving the overall stability of the battery [7].

3.2.3 Carbon-based Carrier Substitution Studies

Conventional carbon blacks (e.g., Vulcan XC-72) are widely used as catalyst carriers due to their excellent electrical conductivity and low cost, but they are prone to electrochemical corrosion under potential fluctuations and high humidity operating conditions, forming carbonyl and hydroxyl functional groups, which in turn lead to catalyst desorption and MEA performance degradation.

Carbon nanotubes (CNTs) represent highly stable carriers due to their highly ordered structure and mechanical strength. Pt particles on CNT carriers maintain a higher electrochemically active surface area (ECSA) in accelerated aging tests, and it was demonstrated that CNT-Pt electrodes can reach a power density of 0.86 W/cm² at 0.7 V, which is superior to that of conventional Pt/C at 0.72 W/cm² [8]. In addition, the porous network structure of CNT facilitates the formation of continuous electron and proton transport paths, which further reduces the ohmic impedance inside the membrane electrode. CNT, as a catalyst carrier, provides a higher specific surface area, and its tubular structure allows for a more efficient electron and proton transport. Zhou et al. demonstrated that Pt catalysts employing CNT as a carrier have a higher catalytic activity and a better catalytic performance than the conventional Pt/C catalytic activity and longer lifetime than conventional Pt/C [9]. In addition, graphene as a carrier material not only has high electrical conductivity, but also effectively enhances the dispersion and stability of catalyst particles through its two-dimensional structure. Yuan et al. showed that Pt-loaded catalysts on electrochemically exfoliated graphene exhibited excellent performance in terms of electrochemical activity and durability, and had the potential to be widely used as novel catalyst carriers in batteries [10].

3.2.4 Ion Channel Distribution Regulation

The ion channel structure of proton exchange membranes directly affects the electrochemical performance of fuel cells. By adjusting the ion channel distribution of membrane materials, the proton conductivity and water management ability of membranes can be enhanced.

The most widely used proton exchange membranes are the Nafion series of fluorosulfonic acid membranes, which have excellent proton conductivity in high humidity environments, but the conductivity decreases significantly at high temperatures (>80°C) or low humidity conditions, which severely restricts their adaptability to practical automotive working conditions. To solve this problem, researchers have commonly adopted the introduction of inorganic hydrophilic fillers into the membranes to enhance the water retention capacity and thermal stability. The use of inorganic fillers such as SiO_2 and TiO_2 doped into Nafion can form more proton-conducting channels inside the membrane, thus increasing the proton conductivity of the membrane. Hu et al.'s research shows that the current density of Nafion membrane with SiO_2 added reaches 100mA/cm2 at a voltage of 1.78V, which is 100% higher than that of ordinary Nafion membrane [11].

In addition to doping modification, the introduction of hydrophilic groups (e.g., sulfonic acid and carboxylic acid groups) into the Nafion backbone using surface grafting has also been shown to improve the water absorption capacity of membranes. By grafting polyacrylic acid or polystyrene sulfonic acid through in situ polymerization,

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the resulting modified membranes were able to maintain a homogeneous wetting structure at elevated temperatures, thus stabilizing their proton conduction pathways [12].

3.3 Analysis of Performance Improvement Effect

3.3.1 Comparison of Power Output of Electric Stacks

The modified membrane electrode achieved a significant improvement in the output power of the electrostack. The study showed that the prepared PtNWS/C catalysts had good electrochemical characteristics. MEA were prepared using PtNWS/C and PtC as cathode catalysts and tested at , and the maximal power densities were 705.6 mW-cm and 674.4 mW-cm, respectively. Energetic stacks of 18 and 20 pieces were assembled using Pt NWS/C and PtC as cathode catalysts and tested at performance. performance tests, the maximum power densities of the electrostacks were 409.2 mW-cm and 702.7 mW-cm, respectively, which indicated that PtNWs/C as a cathodic catalyst exhibited better catalytic activity in the scaled-up membrane electrodes [13].

3.3.2 Stability analysis of membrane electrodes

The stability of the MEA is a critical factor for the long-term operation of fuel cells. This stability can be significantly enhanced by incorporating graphene or nitrogen-doped graphene and optimizing the catalyst structure. Jiang employed nitrogen-doped graphene in place of conventional graphene to modify the catalyst, and in accelerated aging tests, the MEA exhibited a voltage degradation of only 46 mV after 30,000 voltage cycles—markedly lower than the 93 mV observed with traditional Pt/C catalysts—demonstrating a substantial improvement in MEA durability [14].

3.3.3 Changes in efficiency and improved thermal stability before and after modification

Through porous structure optimization and the use of novel catalyst supports, the thermal stability and efficiency of the MEA have been significantly improved. Wang et al. employed the gas diffusion electrode (GDE) method to fabricate the catalyst layer, which exhibited higher porosity and an optimized microporous architecture. Experimental results showed that after 5,000 AST cycles, the power density degradation of the MEA was only 8.40%, and 29.04% after 30,000 cycles—significantly better than conventional catalyst coating methods—demonstrating enhanced durability and electrical conductivity of the MEA [15].

4. Literature References

4.1 Classification and Intelligent Development of Thermal Management Systems

4.1.1 Overview of Active and Passive Thermal Management

Thermal management systems can be categorized into active and passive types according to whether they require external energy input. Active thermal management methods include liquid cooling, air cooling, etc., with the advantages of high control precision and fast regulation response. Liquid cooling system uses deionized water or coolant to circulate inside the electric stack, which has strong heat exchange capacity and is suitable for medium and high power hydrogen fuel cell systems.

The passive thermal management approach relies on the thermal conductivity properties of the material or structure itself without the need for external energy sources, and representative methods include heat pipe and evaporative cooling technologies. Heat pipe structures utilize the phase change of the work material to absorb heat and return it through the capillary structure to achieve efficient heat transfer, and have been widely studied in embedded power reactors.

4.1.2 Intelligent thermal management control technology

To achieve high-precision sensing of the thermal state of the fuel cell system, different types of temperature sensors, such as thermocouples and thermistors, are deployed at key heat sources, including the fuel cell stack, electric drive system, and coolant channels. This enables real-time monitoring of temperatures at various locations, achieving comprehensive monitoring of the spatial temperature field. This multi-point layout, combined with data fusion algorithms, improves temperature measurement accuracy and dynamic response capabilities, enhancing the stability and adaptability of the thermal management system [16].

Conventional PID control is widely used in early fuel cell thermal management systems due to its simple structure and easy implementation, but its response is slow and robust under nonlinear and large hysteresis conditions. In order to improve the system response, researchers introduced a fuzzy control strategy, so that the controller can adjust the PID parameters online according to empirical rules, constituting a fuzzy adaptive PID system, which significantly improves the control accuracy and system adaptability [17].

Further, model predictive control (MPC) techniques are valued for their optimization capabilities and effective handling of system constraints, and MPC responds effectively to sudden changes in load conditions by making rolling predictions of future system states and adjusting actuators such as cooling fans and water pumps in advance. For example, the nonlinear MPC framework developed by Gulewicz et al. allows active prediction and tuning of hybrid thermal management systems, demonstrating superior dynamic performance under different ambient temperatures and load fluctuations [18].

Load-predictive feedforward control is based on vehicle driving data and driving behavior modeling to predict power demand trends for the next few seconds to minutes, thereby adjusting cooling strategies in advance to prevent system overheating or overcooling. The multi-time domain model predictive control (MH-MPC) algorithm proposed by Hu et al. combines short-term and long-term load trends to achieve better energy and thermal management coupling effects [19]. This strategy is particularly suitable for the urban operating environment of FCVs, which frequently change speeds, effectively improving the overall efficiency and lifespan of the fuel cell system. Table 1 is a comparison table of temperature control accuracy and thermal response capability.

Table 1. Comparison table of temperature control accuracy and thermal response capability [16][20-22]

Control program	Temperature control accuracy (K)	Characteristic Advantages	Applicable Scenarios	Applicable Scenarios
Multi-sensor fusion layout	±1.5	100 ~ 400	Precise sensing for improved feedback control	Data support layer for all control systems
fuzzy control	±0.5	<900	Model-less, fast response, robustness	Dynamic load, non-linear fluctuation scenarios
Model Predictive Control (MPC)	±0.2	<750	Highly predictable, highly accurate control, optimized energy efficiency	Stable working conditions, energy saving and optimization demand scenarios
adaptive control	±0.3	401	Automatic adjustment of parameters, Excellent long-term stability	When the system is aging and the environment is changing

4.2 Application and Expansion of Intelligent Thermal Management Systems

4.2.1 Application Status of Intelligent Thermal Management Strategies

The practical application of intelligent control strategies in the thermal management system of hydrogen fuel cell vehicles has been validated on several commercial platforms. Taking the new generation Toyota Mirai as an example, its thermal management system adopts a multi-point temperature sensor layout and incorporates a strategy based on model predictive control (MPC) in order to achieve precise regulation of the cooling system. The system dynamically adjusts the coolant flow rate and fan speed by monitoring the temperature distribution of the electric stack in real time, thereby effectively controlling the temperature difference between the stacks and improving the system's thermal response and overall efficiency. Hyundai's Elec City Fuel Cell bus is also equipped with a variety of intelligent thermal management strategies. These include multi-sensor layout: temperature sensors are arranged at key locations such as the fuel cell stack, electric drive system and coolant channels for real-time temperature monitoring; control algorithms are evolved to optimize the thermal management performance; and load-predictive feed-forward control predicts the future power demand based on the vehicle's driving data and driving behavior, so as to adjust the cooling strategy in advance. The application of these technologies ensures efficient operation of the fuel cell system under various operating conditions.

4.2.2 Scalability of Smart Thermal Management Strategies

Chen et al. proposed a multi-objective decoupled control strategy combined with a non-dominated sorting genetic algorithm (NSGA-II/III) to optimize the controller parameters, which achieves a comprehensive optimization of several performance indexes, such as temperature difference, coolant inlet temperature, and fan power consumption. The strategy exhibits excellent performance in simulation, significantly outperforming the conventional dual-PID control method [23]. In terms of other scalability of the control strategy, the researchers also explored the combination of artificial neural network (ANN) and particle swarm optimization (PSO) algorithms to improve the adaptability and robustness of the control system under complex operating conditions. This data-driven based

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control strategy can achieve higher flexibility and scalability in multi-objective optimization [24]. It can be seen that the intelligent thermal management strategy shows good scalability and multi-objective cooperative control potential in hydrogen fuel cell vehicles.

5. Conclusion

This study systematically investigates the technical pathways and engineering approaches for enhancing the energy conversion efficiency of hydrogen fuel cell vehicles, focusing on membrane electrode modification and intelligent thermal management strategies. On the material side, the introduction of nanocatalysts and highly conductive carbon-based supports significantly improves the catalytic activity and structural stability of the membrane electrode, thereby increasing the power density and operational lifespan of the fuel cell stack.

In terms of thermal management, an integrated control framework combining active cooling and intelligent control has been developed, incorporating key technologies such as multi-sensor fusion layout, model predictive control (MPC), adaptive regulation, and load-predictive feedforward control. These advanced strategies achieve a balanced optimization between temperature control accuracy, thermal response speed, and energy consumption, demonstrating strong engineering feasibility and application potential in commercial fuel cell vehicle platforms.

The synergistic optimization of membrane electrode modification and thermal management further amplifies the overall system performance. Improved thermal uniformity mitigates performance degradation of the membrane electrode materials, while enhanced stack stability reduces the regulatory burden on the thermal management system, forming a positive feedback mechanism.

Future research may further focus on enhancing the high-temperature stability and low-humidity adaptability of membrane electrode materials, while advancing data-driven intelligent control strategies to improve system adaptability and stability under complex and long-term operational conditions. The continuous optimization of both material and system dimensions will provide a solid foundation for the efficient and stable operation of hydrogen fuel cell vehicles, promoting the application and development of hydrogen-powered transportation technologies.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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