Frontier Optimization Strategies for Efficient Fuel Cell Vehicles

Zhengyuan Liu *

School of Applied Chemistry, Dalian University of Technology, Dalian, 116024, China

* Corresponding Author Email: 15753231553@stu.sqxy.edu.cn

Abstract. Fuel cell vehicles (FCVs) represent a pivotal advancement in the evolution of future automobile technologies. This paper introduces a comprehensive approach to enhancing the performance of automotive fuel cells, employing the Predictive Trip Distance Adaptive Equivalent Consumption Minimum Strategy (PTDA-ECMS) objective function for predictive analysis. By developing innovative alkaline electrolyte membranes, catalysts, and electrode materials, and implementing hybrid power system management strategies for fuel cell and battery integration, this study aims to extend fuel cell longevity, improve system efficiency, and reduce operational costs. Additionally, the use of Inductively Coupled Plasma Mass Spectrometry (ICP-MS) for electric catalyst evaluation signifies a methodical exploration into fuel cells with enhanced service life, reduced production expenses, and superior overall performance. Such advancements are anticipated to decrease the operational costs of electric vehicles, thereby increasing marketability and facilitating more sustainable human transportation solutions. This paper provides a detailed overview of effective system optimization methods, including strategies to prolong battery life, alongside a summary of findings and prospects. Through these endeavors, the research underscores the significant potential of FCVs in contributing to the sustainable evolution of the automotive industry.

Keywords: Fuel cell; new energy vehicle; electric vehicle.

1. Introduction

The history of fuel cells can be traced back to the early 20th century. However, in our country, the research and application of fuel cells started relatively late. In recent years, with the country's attention to new energy and technical breakthroughs, the fuel cell industry in our country has made remarkable achievements. Fuel cells have been successfully used in transportation, energy, communication, and other fields, especially in the field of new energy vehicles, the development and promotion of fuel cell vehicles have made certain progress. Because fuel cells have the characteristics of high energy conversion efficiency and environmental friendliness. New energy vehicle batteries are ternary lithium batteries or lithium iron phosphate batteries, lithium iron phosphate batteries generally have a longer life. Under normal circumstances, two main factors affect the battery life of new energy vehicles: the number of charging cycles, the depth of discharge, and the life of the catalyst.

Today's common plug-in hybrid electric vehicle (PHEV) battery capacity is small; service life is also relatively short. The depth of charge and discharge also has a great impact on battery life. Lithium battery has a long life, but it cannot be over-discharged, especially not deeply discharged. If the battery power is kept below 5% but not charged for a long time, the battery will directly "shock", and even cannot be used again [1]. If you leave the battery for more than 15 days after deep discharge, the battery will completely fail. Therefore, this paper will introduce in detail the construction of PTDA-ECMS objective function, replacement of proton exchange membrane and change of catalyst, application of ICP-MS detection of automotive fuel cell electrocatalyst, and method summary to carry out the discussion. This study is of great significance for the practical application of fuel cells to meet the requirements of high efficiency, long life, high safety, and environmental protection.

2. An Effective Way to Extend Battery Life and Optimize the System

2.1. PTDA-ECMS Objective Function

To effectively improve the economy of PHEV and achieve optimal power allocation between fuel cells and power batteries, considering the close connection between driving conditions, battery SOC, equivalence factor, and hydrogen consumption. The PTDA-ECMS objective function was constructed by Lin et al. [2]. The hydrogen consumption of the vehicle was divided into the actual hydrogen consumption of the fuel cell and the equivalent hydrogen consumption of the power battery. Combined with the previous speed prediction, for each time k, the power of the power battery was used as the control variable, and the SOC was used as the state variable, the optimization objective function was constructed as follows.

$$\begin{aligned}\min J = \; & \sum_{t}^{t+H_{\mathrm{p}}}\left(\dot{m}_{\mathrm{H}_2}(P_{\mathrm{FC}}(t),t)+\dot{m}_{\mathrm{B\_equ}}(P_{\mathrm{B}}(t),\mathrm{SOC},t)\right)= \\ & \sum_{t}^{t+H_{\mathrm{p}}}\left(\dot{m}_{\mathrm{H}_2}(t)+k''_{\mathrm{EF}}(t)\frac{P_{\mathrm{B}}(t)}{\mathrm{LHV}_{\mathrm{H}_2}}\right)\end{aligned} \tag{1}$$

where J is the equivalent hydrogen consumption in the predicted time domain, K "EF is the equivalent factor between electric energy consumption and hydrogen consumption, mH_2 is the instantaneous hydrogen consumption of fuel cells, mB-equ represents the instantaneous equivalent hydrogen consumption of power cells, and Hp is the length of the predicted time domain. PTDA-MECS can reasonably allocate the power of fuel cells and power batteries according to the predicted working conditions, make full use of the power of power batteries, reduce the consumption of hydrogen, reduce the cost of battery use, and extend the battery life.

2.2. Change Battery Materials and Upgrade System

2.2.1 Replace the basic proton exchange membrane

At present, proton exchange membrane fuel cells are mainly faced with cost and durability problems from key materials (electrolyte membrane, Pt catalyst, and graphite bipolar plate). Changing the acidic environment inside the battery, that is, using an alkaline electrolyte membrane, can solve this problem well [3]. First of all, in alkaline media, since the redox reaction rate of Pt is faster than that under acidic conditions, the load of Pt can be reduced or replaced by non-noble metal catalysts. In addition, metals can also be selected as bipolar plate materials. Secondly, when methanol is used as fuel, the transmission direction of OH- ion and methanol is opposite, so the methanol permeation phenomenon caused by electrodialysis can be eliminated. As a key component in alkaline fuel cells, the alkaline electrolyte membrane plays a dual function of separating fuel and oxidant and transporting -OH ions. Polyvinyl alcohol (PVA) is a kind of biodegradable polymer material with good film-forming ability and low price. Through polymer blending, the development of a new PVA-based basic composite film with a simple preparation process, low price, and excellent electrochemical performance, and eventually obtaining higher power generation performance, will also be a feasible method to extend the battery life.

2.2.2 Catalytic materials

In the process of preparing new Fe-N-C catalysts by high-temperature pyrolysis, in addition to the formation of single atomic M-Nx sites, metal ions are inevitably reduced and aggregated to form M-NPs. Since the encapsulated M-NPs and M-Nx sites generally coexist, Therefore, N-C-shell-encapsulated M-NPs and M-Nx sites located on the outer carbon shell usually work together [4]. Jiang et al. developed a new high-activity Fe-N-C ORR catalyst containing Fe-N_x coordination and Fe/Fe_3C nanocrystals-Fe@C-FeNC [5]. Fe/Fe_3C nanocrystallites were found to enhance the activity of the Fe-Nx site, and the coexistence of a high content of Fe-Nx with sufficient metallic iron nanoparticles was necessary to improve ORR activity. Zhong et al. prepared MN-doped Fe_3C-NPs, in which the abundant Fe-N_x site and pyridine N make the catalyst have excellent ORR activity and stability [6].

2.2.3 Vehicle fuel cell/battery hybrid power system management

It is found that the optimal combination of hydrogen flow rate and air flow rate, and the optimal combination of cell temperature and humidization temperature are beneficial to improve the performance of PEMFC and promote its application. Based on the optimization management strategy of instantaneous equivalent fuel, Zhou Wei's team formulated the management mode switching rule of a hybrid electric power system and analyzed and calculated the conversion relationship between fuel thermal energy and electric energy and the equivalent fuel consumption of battery power [7]. According to the hybrid power management rules and switching mode and other factors, the initial SOC values of the battery are set to 0.5, 0.6, 0.7, 0.8, and 0.9 respectively, and the real-time simulation test of the system power distribution management under the CYC_HWFET, CYC_MANHATTAN and CYC_UDDS driving cycle conditions is carried out. It is found that when the battery SOC gradually approaches 0.7, the hybrid power system is in the optimal energy allocation state. Adjusting the output power distribution interval of the fuel cell stack makes the fuel cell work more in the high-efficiency region, which is beneficial to improve the fuel economy of the fuel cell stack, to better regulate the rational distribution of power output of multiple energy sources [8].

2.3. Application of ICP-MS in Automotive Fuel Cell Electrocatalyst Detection

The instruments used in this experiment are an inductively coupled plasma mass spectrometer (7900, Agilent Company, USA); Microwave digestion instrument (MARS6, CEM Company, USA); Ultra-pure water machine (Elix Essrntial 5 +Milli-QReference, Merck Millipore, France); Electric heating plate (C-MAG HP10, Aika (Guangzhou) Instrument Equipment Co., LTD.). Pt, Pd, Rh mixed solution: The mass concentration of Pt, Pd, Rh mixed standard solution (National Nonferrous Metal and Electronic Materials Analysis and Testing Center) with nitric acid solution step by step diluted to 0, 10, 50, 100, 200, 500, 1000 μg/L mixed standard solution for use. In solution: The In standard solution (National Center for Analysis and Testing of Nonferrous Metals and Electronic Materials) with a mass concentration of 1000 μg/mL was diluted to 20 μg/L with nitric acid solution for later use. HCl, HNO_3, and HF were all excellent-grade pure, and the experimental water was ultrapure. The fuel cell manufacturer provided an indication value of 1.5207 μg/L for the Pt content in the sample of the automotive fuel cell (the electrocatalyst is Pt). See Table 2 for the working parameters of the ICP-MS instrument. The experimental procedures were as follows: after weighing the sample, grinding it to a powder with a particle size of 0.1 mm, weighing 2 g of the sample, placing it in a Teflon digestion tank, wetted with a small amount of water, and adding acid, and then microwave digestion at 200 ℃. After cooling, it was transferred to a Teflon crucible and placed on a heating plate at 270 ℃ for acid driving. After the viscous shape, add 10 mL aqua regia and continue heating until the solution becomes clear, and then use a nitric acid solution to determine the volume to be measured [9].

Table 1. Working parameters of the ICP-MS instrument

Items	Parameters
RF Transmit power (W)	1550
Atomizing gas flow (L/min)	1.03
Auxiliary air flow (L/min)	0.90
Plasma gas flow (L/min)	15.0
Peristaltic pump speed (r/s)	0.10
Sampling depth (mm)	10.0
Sampling Cone Diameter (Ni)(mm)	1.0
Intercept Cone Diameter (Ni) (mm)	0.4
Sampling pattern	Full quantitation
Scanning method	Jump Peak
Repetitions/samples	3
Detector mode	Pulse/analog dual mode
Oxidation yield (%)	1.876
Double charge (%)	1.134

According to GB/T 20042.4-2009 "Proton exchange fuel cell Part 4: electrocatalyst test method", 195Pt was selected as the isotope to be tested, and In was used as the internal standard. The concentration corresponding to 3 times the standard deviation of the blank sample was taken as the detection limit. The detection limit of 195Pt was 0.0014 μg/L. The standard curve was drawn with the mass concentration of Pt element as the abscissa and the ratio of signals as the ordinate, and the linear regression equations were yPt=0.8121x+0.2544, respectively. The sample solution of the automobile fuel cell (Pt as electrocatalyst) and the mixed standard solution of platinum, palladium, and rhodium were added as the external standard, and the test results of Pt as electrocatalyst were measured in parallel 10 times, and the average value was taken. See Table 2 for the test results of PT as an electrocatalyst. The experimental results will be more effective in helping researchers analyze and improve the catalyst formula, to prolong the life of the catalyst and reduce the cost of fuel cell vehicles [10].

Table 2. Test results electrocatalyst Pt

Elements	Determined value (μg/L)	Standard addition amount (μg/L)	Plus, standard recovery (%)	RSD (%)
Pt	1.5316	2	99.2	0.5

3. Conclusion

Our country is "automobile power", but not "automobile power", facing the great challenge of energy exhaustion and environmental pollution. The automobile industry is a big user of oil consumption and carbon dioxide emission, so the development of new energy technology is imminent. Using the PTDA-ECMS objective function to fully predict the power of the power battery, developing alkaline electrolyte membranes, new catalyst materials, electrode materials, and applying fuel cell/battery hybrid power system to optimize the performance of fuel cell vehicles. The application of ICP-MS to the detection of automotive fuel cell catalysts and other cutting-edge methods has profound significance for the research, effectively extending the battery life and reducing people's use costs. This research is of great significance for fuel cell research and development enterprises and electric vehicle manufacturers and is of great significance for the production of low-cost, long-life, and excellent-performance automotive fuel cells. However, the manufacturing and maintenance costs of new automotive fuel cell systems are relatively high. This mainly stems from the complexity of material acquisition and manufacturing processes, which to some extent limits the feasibility of large-scale commercial production. Second, the raw material supply chain and infrastructure for new fuel cells are insufficient. For example, the production, storage, and distribution of new Fe-N-C catalysts need to establish a sound infrastructure.

However, at present, the construction and operation costs of these infrastructures are high, which limits the promotion and popularization of new fuel cell technologies to some extent. Despite these limitations, fuel cells, as a chemical device that directly converts the chemical energy of fuel into electrical energy, have the advantages of high efficiency and low emissions, so they still have great development potential in saving energy and protecting the ecological environment. With the progress of science and technology and the reduction of cost, it is believed that future research and application of fuel cells will make greater breakthroughs.

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