Service Life and Durability Enhancement Methods of Fuel Cells

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Abstract. This paper focuses on the service life of fuel cells and methods for their improvement. It begins by outlining the limitations of conventional fossil fuels and highlights the advantages of fuel cells in clean energy conversion, emphasizing their high efficiency and renewable characteristics. Subsequently, the study analyzes the primary factors restricting fuel cell lifespan, including electrochemical degradation and environmental influences, and summarizes existing international technological improvements such as novel catalysts, advanced membrane materials, and specialized coatings. The article further proposes comprehensive strategies for enhancing durability across four dimensions: materials, design, operation, and technology. These include developing more stable nanostructured catalysts and alloy catalysts, improving the mechanical and chemical stability of membrane materials, optimizing temperature and humidity control, limiting deep discharge, strengthening online monitoring and maintenance cleaning, and implementing intelligent lifespan extension approaches such as digital twins and self-healing materials. The study underscores the effectiveness of these improvement measures and emphasizes the critical role and broad prospects of fuel cells in the energy transition. It also notes that enhancing longevity remains a key challenge for future research.

Keywords: Fuel cell lifespan; Electrochemical decay; Catalyst; Proton exchange membrane; Self-healing materials.

1. Introduction

Traditional fossil energy sources are not only limited in supply and relatively inefficient, but also produce greenhouse gases such as carbon dioxide and methane. Fuel cells offer a superior alternative to these shortcomings of fossil energy [1]. A fuel cell is a clean energy device that directly converts chemical energy from fuel into electricity through electrochemical reactions. It operates by combining fuel (such as hydrogen or methanol) with an oxidant (such as oxygen) in a process similar to a battery, but without the need for recharging, as long as fuel is supplied continuously. Unlike fossil energy, fuel cells bypass the intermediate steps of "heat energy → mechanical energy," resulting in higher efficiency. Moreover, the fuel can be sourced from renewable energy, reducing reliance on fossil fuels.

However, fuel cell durability degrades under influences such as electrochemical decay and environmental pollution, which affects their lifespan [2,3]. A team from the University of California extended fuel cell service life by embedding platinum catalysts into cobalt oxide. Gore Company enhanced membrane durability by incorporating silicon oxide into Nafion membranes. NASA employed Au–Pd bipolar plate coatings to achieve a fuel cell lifespan exceeding 60,000 hours. In China, research institutions and companies have developed anti-corrosion cathode catalysts and intelligent thermal management systems, increasing fuel cell longevity to over 15,000 hours. These four approaches have gained international recognition and adoption.

Based on cutting-edge research in fuel cell lifespan prediction and health management, along with recent advances in hybrid vehicle energy management, this paper proposes a comprehensive optimization strategy to enhance fuel cell service life. The approach covers four

dimensions—materials, design, operation, and technology—while taking environmental benefits into account.

2. Materials

2.1. Development of Novel Catalyst Materials

Novel catalyst materials, such as nanostructured catalysts and alloy catalysts, are developed to significantly enhance their stability and anti-degradation performance. Through specialized nanoscale structural design, phenomena such as carbon deposition, and agglomeration on the catalyst surface can be effectively reduced, while resistance to impurity poisoning is improved. Advanced immobilization techniques are employed to modify catalyst loading technology, substantially minimizing catalyst loss during operation [4]. For example, Toyota utilizes platinum-cobalt (Pt-Co) alloy nanoparticle catalysts in its fuel cell systems. By precisely controlling the alloy ratio and particle size within the 3–5 nm range, the electrochemically active area is increased to 350 square meters per gram of platinum—twice that of conventional platinum catalysts—while the boiling point is raised to above 120°C. Meanwhile, Ballard Power Systems has developed a platinum-palladium core-shell structured catalyst (Pt@Pd). Using specialized atomic layer deposition technology, a uniform palladium shell is formed around the platinum core, reducing platinum exposure by 60%, decreasing the risk of carbon monoxide poisoning by 40%, and extending the system lifespan to 15,000 hours [5].

2.2. Improvement of Proton Exchange Membranes Using High-Conductivity Materials

The addition of nanoparticles such as SiO_2 and TiO_2 into Nafion membranes to form composite membranes significantly enhances the overall performance of the membrane material. The incorporation of these nanoparticles effectively reduces radical attack while improving mechanical strength and chemical stability, preventing degradation under high-temperature and high-humidity conditions [6].

Furthermore, cerium oxide (CeO_2) nanoparticles can be added to the membrane as radical scavengers. Using a soul-gel method, CeO_2 nanoparticles are uniformly dispersed within the membrane matrix, forming an effective radical quenching network that further delays chemical decay [7]. Experimental data show that composite membranes with 2% CeO_2 exhibit a 40% longer lifespan compared to conventional membranes in accelerated aging tests [8].

2.3. Conductive Polymer Coatings on Bipolar Plate Surfaces

Coating titanium plates with gold or applying conductive polymers such as polyaniline to graphite plates can effectively prevent corrosion products from contaminating the catalyst, reduce contact resistance, and improve system efficiency and lifespan. By optimizing the coating process and thickness, an optimal balance between corrosion resistance and electrical conductivity can be achieved.

Audi employs magnetron sputtering technology to deposit a 2-micrometer gold layer on the surface of its fuel cell bipolar plates. Through precise control of process parameters such as a sputtering power of 200 W and a working gas pressure of 0.5 Pa, the contact resistance is reduced to below 10 $m\Omega \cdot cm^2$, and the corrosion current density is successfully lowered to 0.1 $\mu A/cm^2$. SGL Carbon has developed polyaniline-coated graphite plates using an electrochemical polymerization method to form a uniform polyaniline coating on the graphite surface. This approach reduces costs by 80% compared to gold plating, improves corrosion resistance by 50%, and maintains contact resistance below 15 $m\Omega \cdot cm^2$, achieving an excellent balance between performance and cost [9].

3. Design

3.1. Real-Time Adjustment of Temperature and Humidity

Real-time regulation of inlet air humidity (relative humidity 80%–100%) and stack temperature (60–80°C) can effectively prevent drying or flooding of the proton exchange membrane. Precise control of temperature and humidity is achieved through a network of high-precision sensors and an intelligent control system.

Hyundai Motor Company employs a multi-stage humidification system in its fuel cell vehicle NEXO, equipped with high-precision humidity sensors (accuracy ±2% RH) and temperature sensors (accuracy ±0.5°C). Using multi-stage membrane humidifiers, it precisely controls the cathode inlet humidity at 95% and outlet humidity at 80%, maintaining the membrane water content at an ideal state of 14 water molecules per sulfonic acid group. Plug Power Inc. optimizes flow field design and utilizes 3D printing technology to manufacture bipolar plates with a graded temperature distribution. This creates a temperature gradient from 65°C to 75°C within the stack, effectively avoiding local liquid water accumulation and improving water management efficiency by 30%.

3.2. Limiting Deep Discharge

Operating the battery system within a state of charge (SOC) range of 20% to 80% can prevent electrode corrosion caused by the oxygen evolution reaction induced by deep discharge. The poisoning effect of impurity gases on the catalyst is further reduced by installing advanced gas purification devices.

Honda Motor Company strictly controls the SOC operating window between 25% and 85%, with real-time monitoring by a high-precision battery management system (BMS) at a sampling frequency of 10 Hz. Simultaneously, a palladium membrane purifier equipped with a 0.5-micrometer-thick palladium-silver alloy membrane reduces CO concentration to below 0.05 ppm at an operating temperature of 300°C, extending the anode catalyst lifespan by 30%. Robert Bosch GmbH has developed a novel PROX reactor utilizing a CuO-CeO catalyst. By optimizing the catalyst support structure and active site distribution, the reactor achieves a CO preferential oxidation efficiency of over 99.9% within an operating temperature range of 150–200°C, with a space velocity of 10,000 h^{-1}.

4. Operation

4.1. Implementing Online Monitoring for Timely Adjustments

A comprehensive online monitoring system is established to periodically detect membrane water content and catalyst activity decay. By integrating big data analytics, real-time system status monitoring and early warning are achieved. High-frequency data acquisition and intelligent analysis enable the early detection of potential issues.

Bloom Energy has developed a multi-parameter online monitoring system that performs a full electrochemical impedance spectroscopy (EIS) scan every 500 hours, covering a frequency range from 10 mHz to 10 kHz, enabling accurate assessment of membrane hydration and catalyst activity. Simultaneously, a voltage monitoring system with a sampling interval of 1 second employs machine learning algorithms to analyze voltage decay trends. An early warning is automatically triggered when the voltage decay rate of a single cell exceeds 2 mV per 100 hours, allowing prediction of membrane drying risks up to 200 hours in advance. Shanghai Hydrogen Horizon Energy Technology Co., Ltd. has developed a cloud-based monitoring system that collects over 20 parameters in real time, including voltage, temperature, and pressure. Using deep learning algorithms to establish degradation models, the system achieves an early warning accuracy rate of over 95% [10].

4.2. Adopting Proper Maintenance and Cleaning Methods

Scientific maintenance and cleaning procedures are established to periodically remove contaminants from electrode surfaces. Appropriate protection measures are implemented during long-term shutdowns to effectively slow down material aging rates. By optimizing cleaning processes and storage conditions, the system's lifespan is significantly extended.

Ballard Power Systems has developed a dedicated cathode cleaning protocol, which performs cyclic flushing every 2,000 hours using a solution of 0.5% hydrogen peroxide and 0.1M dilute sulfuric acid. The flow rate is controlled at 2 L/min, the temperature is maintained at 40°C, and the cleaning duration set to 30 minutes, achieving a sulfide removal rate of over 95%. Toyota Motor Corporation has implemented strict storage specifications: during extended shutdowns, the system temperature is controlled at -10°C, the environment is filled with high-purity nitrogen (99.999% purity), and humidity is kept below 10% RH. These measures reduce the monthly decay rate from 3% to 0.5%. Additionally, regular activation operations are conducted, including a full start-run-shutdown cycle every three months to maintain system activity.

5. Technology

5.1. Application of Novel Self-Healing Materials

New materials with self-healing functionality are developed and applied. By embedding functional microcapsules or healing agents within the material, automatic repair of damaged areas is achieved, significantly enhancing durability and reliability.

When cracks occur in the electrode, the microcapsules rupture and release healing agents. Under ambient humidity, hydrolysis-condensation reactions take place, forming a cross-linked siloxane network. This enables a repair efficiency of 80% for cracks as wide as 0.1 mm. After 1,000 thermal cycles, electrodes with self-healing materials exhibit a 60% reduction in performance degradation compared to conventional electrodes. This technology has demonstrated durability over 3,000 cycles under laboratory conditions and is currently advancing toward industrial application [11].

5.2. Development of Intelligent Algorithm Assistance

Advanced digital twin technology and artificial intelligence algorithms are employed to establish high-precision virtual models, enabling real-time monitoring, prediction, and optimization of actual systems. This significantly enhances operational efficiency and lifespan.

The virtual model developed by Bosch utilizes a multi-physics coupling approach to accurately simulate electrochemical, thermal, and fluid behaviors, achieving a prediction accuracy of 95%. By leveraging model predictive control (MPC) algorithms to optimize operational parameters in real time, the system lifespan is extended from 15,000 hours to 18,000 hours, with a 5% improvement in efficiency [12]. The National Renewable Energy Laboratory (NREL) developed a flooding prediction model based on an LSTM deep learning network. With 32 input feature parameters and over 1 million training data samples, the model achieves a prediction accuracy exceeding 92%, provides early warnings of flooding risks 30 minutes in advance, and reduces failure rates by 70% [13].

6. Conclusion

In summary, fuel cells represent one of the most promising energy and clean energy conversion devices of the new era, with broad application prospects in the energy sector. However, their widespread service life remains limited by multiple factors, posing significant research challenges.

At the material level, developing novel catalyst materials, improving membrane materials, and applying conductive polymer coatings on bipolar plates can significantly enhance the internal electrochemical reaction environment of fuel cells, reduce material corrosion and degradation, and

thereby extend their operational life. For example, advanced catalyst's lower reaction activation energy, improve catalytic efficiency, reduce the usage of precious metals, and enhance durability while cutting costs.

From a design perspective, controlling operating temperature and humidity and limiting deep discharge can effectively prevent fuel cells from operating under extreme conditions, reducing performance degradation caused by environmental factors and over-discharge. Proper temperature and humidity management maintains the proton exchange membrane's performance and ensures ion conductivity, while restricting deep discharge alleviates stress on electrodes and catalysts, delaying the aging process.

Online monitoring during operation and appropriate maintenance and cleaning methods are equally critical. Real-time monitoring enables a comprehensive understanding of the fuel cell's operating status, facilitating timely detection of abnormalities and adjustments to prevent failures, thereby reducing overall load and wear. Regular and proper maintenance cleanses impurities and by-products within the cell, preserving the functionality and longevity of its components.

This study provides an in-depth analysis of the factors limiting fuel cell lifespan and proposes effective strategies for its enhancement, establishing a theoretical and technical foundation for large-scale application in the energy field and supporting the transition to clean energy. Future efforts should focus on breakthroughs in material innovation and intelligent system integration, such as exploring more efficient self-healing materials and building end-to-end smart operation and maintenance systems. These advances will further extend fuel cell service life, expand application scenarios, and inject stronger momentum into the development of green energy.

7. Authors Contribution

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

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