

PAPER

The Applications of Platinum Catalysts in PEM Fuel Cells: Process and Data Analysis

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ABSTRACT

Achieving global carbon neutrality and reducing airborne pollution require innovative solutions. One potential solution is to replace fossil fuel-based energy with clean energy production and supply, necessitating the advancement of fuel cells, metal-air cells, supercapacitors, and water splitting. This paper analyzes data and predicts future trends for the quality of catalysts, carrier structure, construction characterization, environmental impact, and recycling preparation techniques for waste platinum catalysts. The findings presented in this study serve as inspiration for related research, aiding the successful promotion of clean energy technologies.

KEYWORDS

carbon neutrality, fuel cells, clean energy production, carrier structure

1 INTRODUCTION

Fossil energy sources are being overused and exploited to an increasing extent due to economic development and population expansion, which is leading to environmental challenges and a lack of energy resources [1–3]. Global demand for natural energy has surged by 45% over the past two decades, according to BP's basic estimate. With an average annual growth rate of 1.7%, this percentage is predicted to increase up to 39% during the next 20 years. China is both the world's biggest energy user and the market with the most substantial primary energy growth, accounting for 23% of global consumption and 61% of global growth. The ratio of coal and oil storage to extraction in China is 30 and 11.9 years, respectively, according to government statistics [4]. Therefore, the creation of clean and renewable new energy is the only solution for sustainable human development given the aspect of the demand for energy brought on by the increase in the global economy and population [5–7].

To generate electricity, fuel and air are fed into the fuel cell [8–10]. Because they can convert chemical energy from fuel directly into electrical energy without burning or altering the energy type, fuel cells have a high conversion efficiency. In addition, the popularity of fuel cells is growing due to their mobility and environmental

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friendliness. In the twenty-first century, they are currently recognized as the preferred, clean, and effective power-generating technology [11].

Fuel cells were first proposed by Sir William Robert Grove in 1839. From early studies on concepts, materials, and principles to their initial implementation in the 1960s as the primary power source for the moon missions, they are now used as a power source for electric cars using proton exchange membrane fuel cells [12].

The three main types of fuel cells are proton exchange membrane fuel cells (PEMFC), alkaline fuel cells (AFC) and molten carbonate fuel cells (MCFC). There are two other types of fuel cells: solid oxide fuel cells (SOFC) and phosphoric acid fuel cells (PAFC) [11–13]. PEMFC seems appealing due to their low operating temperature, high energy conversion efficiency, superior conductivity, and durability [14–16]. However, their practical applications are still limited because of the expensive precious metals used as catalysts, poor stability, short lifespan, and high cost. Recent developments in anion exchange membrane technology have led to the increased popularity of anion exchange membrane fuel cells. By permitting the fuel cell electrode reaction to occur in an alkaline environment and enabling the use of non-precious metal catalysts, anion-exchange membrane fuel cells may substantially reduce the cost of fuel cells [17–19]. However, low energy conversion efficiency is still a problem with anion-exchange membrane fuel cells. This is because of their relatively weak electrical conductivity [20–21].

The development of more effective fuel cells capable of utilizing non-precious metal catalysts, as well as the production of cheaper fuel cell catalysts and their reduced pricing, play a crucial role in advancing fuel cell technology [22–23].

In contemporary fuel cells, platinum-based catalysts are commonly utilized in the cathodic oxygen reduction. Although platinum catalysts possess strong catalytic activity for catalytic oxygen reduction, they are expensive and exhibit weak methanol resistance [24–25]. Consequently, the metal utilization rates and availability of precious metals, as well as the exploration of non-precious metal catalysts as potential substitutes for precious metal catalysts, have been extensively studied both domestically and internationally. Carbon materials have been employed as carriers in the production of platinum catalysts to promote a more uniform dispersion of platinum particles and reduce their size [26]. To boost the use of Pt catalysts, several researchers have proposed changing the carbon carriers [27–28]. Much of the non-platinum catalyst research has focused on non-precious metal catalysts loaded with heteroatoms and non-precious metals such as Fe and Co, and others [29–31]. However, non-precious metal catalysts still exhibit lower catalytic activity compared to Pt catalysts and require further improvement in terms of stability. Therefore, research on easily accessible Pt catalysts and non-Pt catalysts with high catalytic activity will play a crucial role in determining the commercial viability of large-scale fuel cell deployment, given the current state of fuel cell catalysts.

2 CATALYST PERFORMANCE STUDY

In order to gain a better understanding of the relationship between the structure and properties of materials and to develop Pt-based nanomaterials with exceptional performance, Li Pangquan et al., conducted a study [32]. They investigated the controllable preparation method, formation mechanism, and physicochemical properties of Pt-based nanomaterials. The findings of this research are vital for the advancement of the practical applications in related technologies. It is imperative to promote the use of these technologies in real-world applications.

Figure 1 presents octahedral Pt-Ni/C alloy and highlights their enhanced activity in ethanol oxidation process when compared to Pt-Sn catalyst alone by the addition of Mo [34]. Additionally, the introduction of a third transition metal element, Rh, in a

specific riation with Pt and Sn catalysts, has the potential to significantly enhance C-C bond breaking and thereby increase CO₂ selectivity. This is particularly relevant as the primary product obtained using Pt and Sn catalysts alone is acetic acid, which exhibits limited C-C bond breaking capability [35]. Figure 2 displays TEM images of the porous micro polycrystalline structure at both low and high magnifications. The connected Pt nanocrystals are uniformly distributed across the NiOx species. Due to the creation of a 3D model porous nanostructure of Pt-NiOx [36], which is made of linked Pt nanocrystals and amorphous NiOx species, and the surface oxide, which significantly increases the electrocatalytic activity of Pt-based nanomaterials, Pt-NiOx/C has a significantly greater current and excellent stability when compared to Pt/C catalyst at 0.45 V (vs SCE). The 3D porous structure that has been built will provide the catalysts excellent stability.

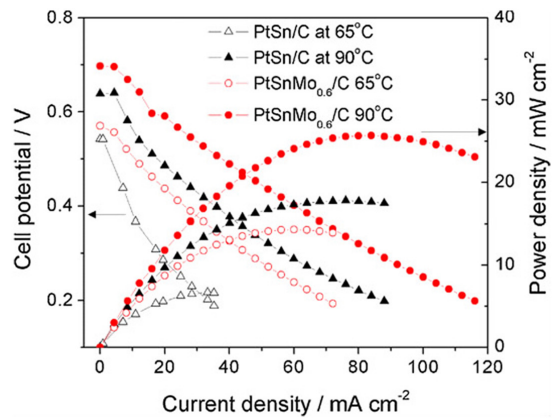


Fig. 1. Comparison of the DEFC performance of the PtSn/C and PtSnMo_{0.6}/C [32]

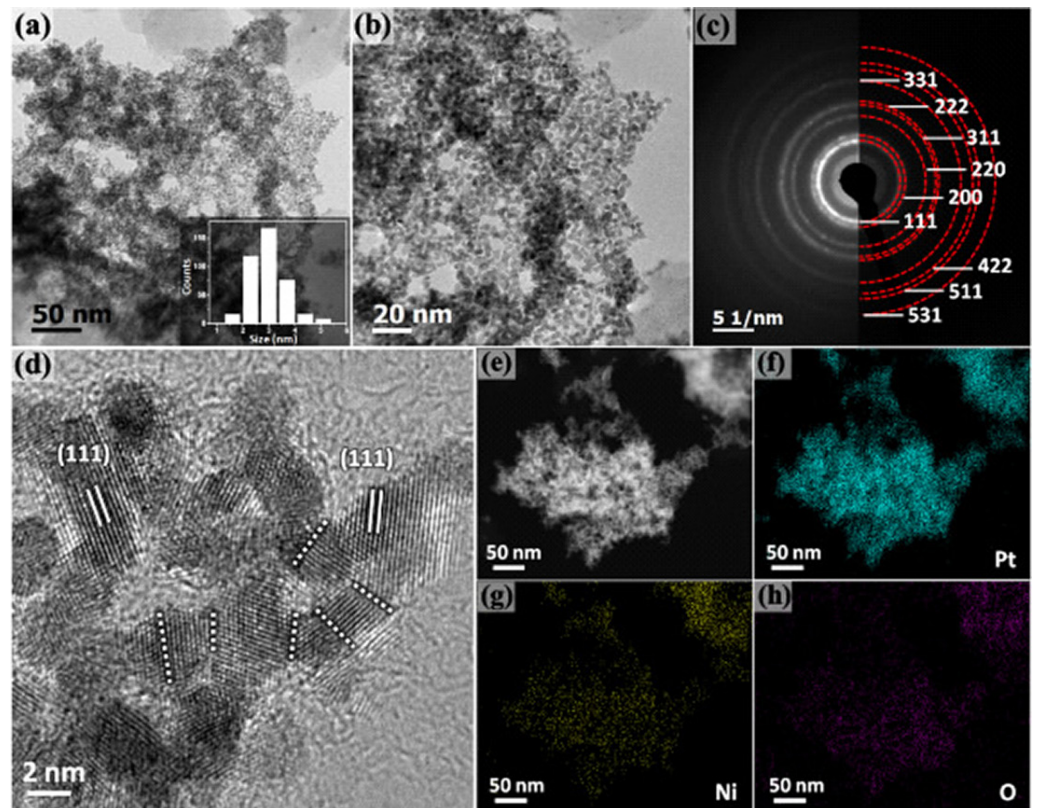


Fig. 2. Map of a porous nanostructure [32]

3 APPLICATION OF MESOPOROUS MATERIALS AS FUEL CELL CARRIERS

A catalyst carrier should possess characteristics, including good corrosion resistance, a well-defined pore structure, a high specific surface area (with more mesopores to facilitate gas and mass transfer), and solid electrical conductivity [37]. Among the commonly utilized carriers, Vulcan XC-72 carbon black, Ketjen Black, Black Pearls 2000, Acetylene Black, and Macsorb are frequently used commercial carriers. Notably, Vulcan XC-72 carbon black is the carrier of choice in over 80% of cases when investigating loaded electrocatalysts [38]. The number of catalytic active sites and activity are decreased in practical applications due to the uneven pore size distribution of commercial carriers, the presence of additional microporous structures, limited catalyst dispersion, corrosion of carbon carriers during the reaction, agglomeration, and shedding of catalyst particles [39–40]. To address these challenges, researchers are focusing on high-activity mesoporous materials with a well-defined pore structure and a high specific surface area. These materials offer higher electrical conductivity, mechanical stability, and void structure that enable evenly distributed and uniform loading of metal nanoparticles and accelerate electron transmission [41]. Consequently, there is a current emphasis on developing new mesoporous material carriers and altering existing ones, as this field of research holds significant promise for improving catalyst performance.

The development of catalysts with higher activity can be studied in terms of catalyst active substances and carriers. For example, multi-metal catalysts, carriers with better stability structures, and noble metal/oxide series catalysts created through doping and coating techniques can be used to create catalysts with enhanced activity, thereby significantly increasing their catalytic performance. In addition to raising catalyst activity and reducing the number of noble metals, mesoporous materials may also promote metal dispersion, which is crucial for enhancing catalytic activity. By altering the synthesis process, it is possible to significantly increase the surface area of mesoporous materials, minimize the pore size dispersion, and strengthen the binding with the catalyst. The utilization of unique mesoporous materials is expected to be a prominent trend in future fuel cell technologies. By exploring and optimizing mesoporous materials, researchers can unlock new possibilities for catalytic applications in various fields, including fuel cells.

4 CATALYST PREPARATION AND CHARACTERIZATION STUDIES

Study revealed that by raising the electron density of Pt while simultaneously lowering the amount of strong acid sites, and preventing the sintering of Pt particles, increases the catalytic dehydrogenation activity, stability, and olefin selectivity of low carbon alkanes. According to research done by Qui Yi et al., [43] on the effects of different levels of Fe additive on the effectiveness of Pt/Sn-SBA-15 catalytic propane dehydrogenation, adding the right amount of Fe to the catalyst may boost the catalytic dehydrogenation activity of propane. However, too much Fe would encapsulate on the Pt metal particles' surfaces, limiting Pt dispersion and thereby lowering the activity of the propane catalytic dehydrogenation reaction.

Figure 3 displays the XRD patterns of the catalysts before and after the introduction of the additive. The results indicate that the peaks corresponding to the reactive Pt species did not significant changes upon the addition of the additive. However, in

the PtFe₂/Sn-SBA-15 and PtFe₄/Sn-SBA-15 samples, the peaks associated with SiO₂ exhibited some modifications, particularly in the wide peak around 25°. This observation suggests that the pore structure of the catalyst may have collapsed during the reaction.

By analyzing the amount of deposited coke using TG analysis in an air environment, Figure 4 illustrates the weight-loss behavior of the reacting catalysts. In case of Pt/Sn-SBA-15, a consistent weight loss is observed at 220°C. However, with the adding of additives, the weight loss range shifts between 500°C and 550°C.

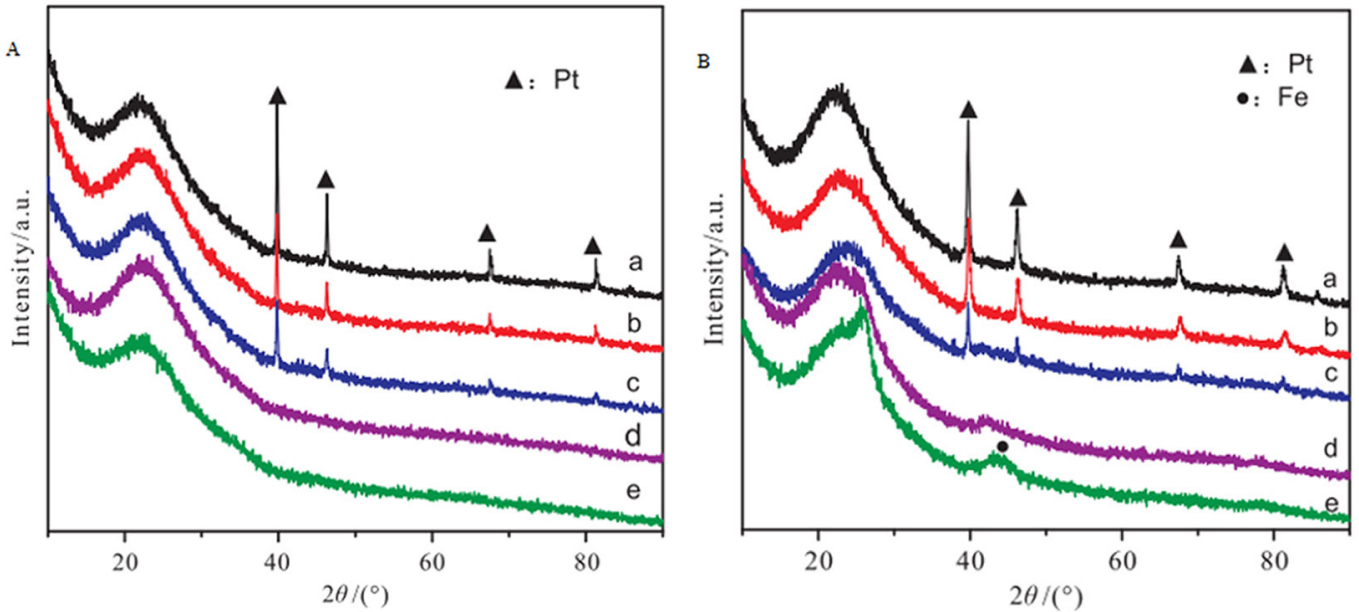


Fig. 3. Before A: reaction; after B: reaction in the XRD spectrum of the catalyst [43]

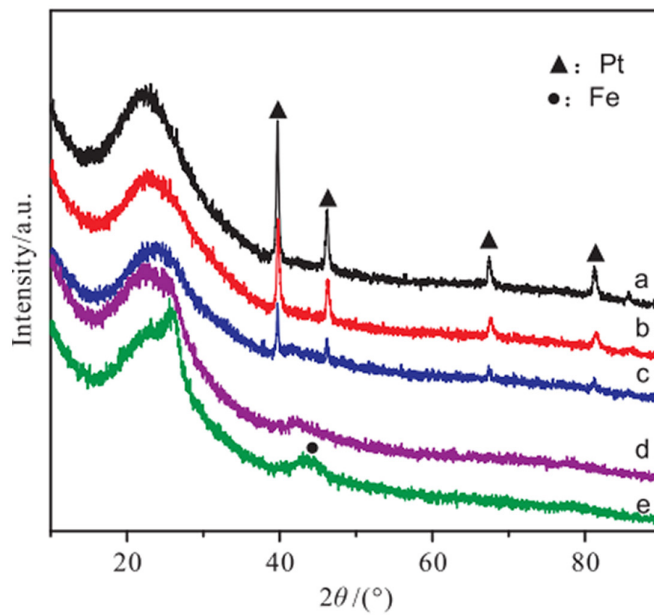


Fig. 4. The TG-DTG curve of the catalyst after the reaction [43]; (a) Pt/Sn-SBA-15; (b) PtFe0.5/Sn-SBA-15; (c) PtFe1/Sn-SBA-15; (d) PtFe2/Sn-SBA-15; (e) PtFe4/Sn-SBA-15

5 THE ENVIRONMENTAL IMPACT OF PLATINUM CATALYST SCRAP AND RECYCLING TREATMENT

Due to their rarity and high cost, precious metals are referred to as “secondary resources” and have a greater recycling value compared to common metals. Platinum, in particular, is found in very limited quantities within the Earth’s crust, thus it is crucial not to squander finite supplies. These resources will surely have an influence on the ecosystem, including the land, water, air, etc., if they are not retrieved.

Secondary platinum group metal resources are generated after the platinum group metals have undergone processing and have utilized in the production of various goods. Unlike primary platinum ores, these secondary resources exist in a variety of forms and compositions, allowing for easier chemical compositions, quick recovery times, and most cost-effective investments. Among the significant secondary sources, vehicle exhaust catalysts stand out as a crucial source for the recovery of platinum group metals [44–48]. The regeneration and recovery of platinum group metals from secondary sources have emerged as a substantial supply of these metals.

6 DATA ANALYSIS AND FUTURE TRENDS

In recent years, the significance of recycling of platinum catalyst waste has grown substantially due to the limited availability of platinum and the adverse environmental impact of mining and refining processes. The data analysis conducted in this study reveals that recycling of platinum catalyst waste can significantly reduce the demand for new platinum resources while simultaneously mitigating the environmental impact of platinum mining and refining.

Moreover, the future trend for platinum catalyst waste recycling appears promising. With technological advancement and for a growing emphasis on clean energy, the demand for platinum catalysts in applications such as fuel cells, metal-air cells, supercapacitors, and water splitting is expected to increase. This, in turn, will create a huge potential market for platinum catalyst waste recycling, which can not only reduce the cost of platinum catalysts but also contribute to the sustainable development of the environment. Therefore, it is necessary to further explore the recycling techniques and optimize the recycling process to meet the increasing demand for platinum catalysts in the future.

In addition, this study introduces a novel approach to recycle platinum catalyst waste by using a combination of pyrolysis and hydrometallurgy. The findings demonstrate that this approach enables a high recovery rate of platinum and other valuable metals from the waste, while also minimizing the production of harmful byproducts. The potential application of this approach in large-scale industrial platinum catalyst waste recycling presents a sustainable and cost-effective solution for the platinum industry.

Additionally, the economic analysis conducted in this study demonstrates the significant economic benefits associated with recycling platinum catalyst waste to the industry. By reducing the reliance on new platinum resources, the recycling process effectively lowers the cost of platinum catalysts and increases the competitiveness of the industry. Moreover, the environmental benefits of platinum catalyst waste recycling can enhance the corporate social responsibility of the industry and improve its reputation in the market.

This study, thus, highlights the importance and potential of platinum catalyst waste recycling as a means to achieve sustainable development within the platinum industry. The proposed approach of pyrolysis and hydrometallurgy can be a promising solution for industrial-scale platinum catalyst waste recycling. Further research and development in this area can contribute to the sustainable development of the environment and the economy.

7 CONCLUSION

In conclusion, the data analysis and future trend analysis indicate that proton exchange membrane fuel cells have great potential for widespread application in various fields. Nonetheless, the high cost and scarcity of precious metal electrocatalysts, such as platinum, pose significant challenges to the commercialization of fuel cells. To address these challenges, it is essential to increase the utilization rate and lower the loading of platinum in fuel cells. Furthermore, effective recycling of secondary resources of platinum group metals is crucial to prevent resource waste and environmental pollution.

In the future, the demand for platinum group metals is expected to increase due to the growing popularity of fuel cells and other clean energy technologies. Therefore, the recycling of platinum group metals from waste materials, including spent fuel cell catalysts, will become increasingly important. The development of innovative and efficient recycling technologies will not only reduce the dependence on primary resources but also contribute to the sustainable development of the environment and the economy.

In summary, the utilization rate and loading of platinum in fuel cells must be optimized, and effective recycling of secondary resources of platinum group metals must be implemented to promote the commercialization of fuel cells and achieve sustainable development in the energy industry.

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9 AUTHOR

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