Research on Technological Development Status of New Energy Vehicles Based on Hydrogen Fuel Cells

Ma Sining1,∗, Shen Peigen2*

1 Tianjin Light Industry Vocational Technical College, Jinnan, Tianjin, China
2 Zhangjiakou Power Supply Company, State Grid Jibei Electric Power Company Limited, Zhangjiakou, Hebei, China

∗email: tjqgmsn@tjlivtc.edu.cn

Abstract: As an electric energy conversion medium with economic value, hydrogen energy, which is storable and highly adapted to new energy, can be used as an energy storage medium to ensure the stable output of energy and the continuous running of vehicles in the context of the continuous deterioration of the global environment and the constant decline of the total amount of traditional fossil fuels. This paper summarized the development status of hydrogen fuel vehicles and development characteristics of corresponding technologies, and studied the technological development status of hydrogen fuel cell vehicles (HFCEVs) through the analysis of hydrogen energy for vehicles and through summaries of the development of hydrogen fuel vehicles and key technologies of hydrogen fuel cells.

1. Introduction

Hydrogen vehicles refer to cars with hydrogen as the energy source, and the energy contained in hydrogen is applied directly or indirectly to the automotive field in different forms.

Hydrogen vehicles can be divided into two types by the use of hydrogen energy: first, hydrogen internal combustion engine vehicles (HICEVs) which are driven by the power generated by hydrogen combustion in the internal combustion engine; second, Fuel cell vehicles (FCEVs), which are driven by a motor propelled by currents formed by electrons from the reaction of hydrogen or hydrogen-containing substances with oxygen in the air in fuel cells.

HICEVs are more common as a hydrogen storage device is simply added on the basis of traditional vehicles. However, the limited capacity of the hydrogen storage device results in the requirement for frequent hydrogen refueling of hydrogen fuel vehicles. Meanwhile, CO₂ emissions are unavoidable and there is a safety problem about hydrogen storage, which is not in line with the current environmental development trend, as they are modified from traditional vehicles. Therefore, HICEVs cannot become the mainstream of future development.

In comparison with HICEVs, FCEVs use hydrogen energy to generate electricity and electric energy is converted into mechanical energy to drive the vehicles. Hydrogen fuel cells truly achieve zero emission and zero pollution based on the characteristics of hydrogen energy[1].

Hydrogen energy is an ideal energy source in the new energy system, which, in comparison with other new energy, avoids the disadvantage of intermittency and has a higher calorific value. Its density (140MJ/kg) is as high as twice that of solid fuel (50MJ/kg). Moreover, the product of hydrogen energy
is water, which has zero pollution to the environment. Hydrogen energy is the most environmentally friendly energy, which can be stored in high-pressure tanks in the gaseous phase. It can also be stored in the liquid phase and in the solid state such as porous materials, metal cyanides and complex hydrides.

The application of hydrogen energy as an energy carrier in the automotive field has the following advantages:

1) High-efficiency conversion between hydrogen and electric energy can be achieved through water electrolysis technology;
2) Compressed hydrogen and hydrogen energy stored in the solid state have a high energy density; and
3) Zero pollution of vehicles can be realized based on the characteristics of hydrogen energy, making hydrogen fuel vehicles become new energy vehicles in the true sense.

2. Development status of hydrogen fuel vehicles

Low carbon transition and green development have become the main theme of future economic development according to the analysis of global economic and energy development trends. President Xi Jinping stated "China will increase its intended nationally determined contributions, work out more powerful policies and measures and strive to reach the peak of CO₂ emissions by 2030 and achieve carbon neutrality by 2060" in the Speech of Xi Jinping at High-level Meetings to Commemorate the 75th Anniversary of the United Nations. The development of hydrogen energy and the promotion of hydrogen fuel vehicles have become an important part of the future economic development in various countries [²].

2.1 Summary of the development status of global hydrogen fuel vehicles

The United States, Japan, the European Union, South Korea and other countries and regions have released national hydrogen development plans successively, clarified the development trend of hydrogen energy, and enhanced the research and development of hydrogen fuel-based new energy vehicles and the support for enterprises continuously. Global hydrogen fuel-based new energy vehicles will usher in a period of rapid development.

According to the latest research results released by the Hydrogen Council, it is estimated that there will be 30 million hydrogen energy-related jobs worldwide and the use of hydrogen energy will reduce about 6 billion tons of CO₂ emissions by 2050. Hydrogen energy can create a market value of USD 2.5 trillion, accounting for up to 18% in the global energy system.

As the most strategically significant energy among new energy resources, hydrogen energy has received more and more attention from organizations, regions and countries. Eighteen economies, accounting for 70% of the world’s total economy, have formulated hydrogen-related energy development strategies according to statistics from the authority [³].

Hydrogen fuel cells are developing rapidly under the stimulation of policies of various organizations, regions and countries around the world. According to a conservative estimate, there were up to 25,210 new energy vehicles based on hydrogen fuel cells around the globe as of 2019. The sales volume was 12,350 in 2019, a year-on-year increase of 212%. The global hydrogen fuel-based new energy vehicles are showing a high profile growth.

2.2 Summary of the development status of hydrogen fuel vehicles in China

Hydrogen fuel vehicles have grown fast in China in recent years, with a total investment of more than RMB 100 billion. In general, the scale of China’s hydrogen fuel vehicle industry has continued to expand with distinguished features such as cross-border layout and the introduction of simple technology projects. Hydrogen fuel vehicles have seen positive signals such as the marketing of hydrogen fuel cells and the quality improvement of industrial investors in China since 2021. Hydrogen fuel vehicles and hydrogen refueling stations have continued to increase with the emergence of demonstration cities for thousand-level fuel cell vehicles such as Shanghai and Foshan. 7,200 hydrogen
Fuel vehicles were put into operation and more than 80 hydrogen refueling stations were built as of 2020. A new situation has emerged in the development of hydrogen fuel vehicles under the environment of continuously released policies [4].

Hydrogen energy was first proposed in the 2019 government report, and was included in the definition of energy for the first time in the Energy Law of the People's Republic of China (draft for comments) in April 2020, which is an important point for the development strategy and supporting policy for hydrogen fuel cells in China. In November of the same year, the Development Plan of New Energy Vehicle Industry (2021-2035) clearly pointed out that efforts would be made to achieve the commercial use of hydrogen fuel vehicles with hydrogen fuel cells as an important component in 2035 [5]. The Notice on Pilot Application of Fuel Cell Vehicles was officially released in September 2020, which proposed to strive to master key technologies of hydrogen fuel vehicles and build a complete industrial chain gradually by 2025.

More than 40 provinces and cities have made development plans for hydrogen fuel up to now. China has initially established a hydrogen industrial chain of hydrogen fuel cell vehicles with grey hydrogen as the main hydrogen source and high-pressure hydrogen as the main carrier based on the development status of hydrogen fuel. Hydrogen fuel vehicles in China now have the foundation for high-quality development, mainly manifested in the following:

1) The top-level design of the industry of hydrogen energy for vehicles has gradually become clear and government support has been continuously improved;
2) The demonstration operation of hydrogen fuel vehicles in key development regions has achieved great results, and fuel vehicles have strong demonstration and promotion capabilities;
3) Continuous breakthroughs have been made in key technologies. Fuel cell materials have been domestically produced, and hydrogen production technology based on renewable energy has been improved continuously.

3. Key technologies of hydrogen fuel vehicles

3.1 Hydrogen production technologies for hydrogen fuel vehicles

Hydrogen production technologies include fossil fuel restructuring, decomposition, photolysis and water electrolysis. The global annual hydrogen energy consumption is about 4 billion tons currently. More than 95% of the hydrogen is obtained from fossil fuels. On the one hand, traditional fossil fuels have the disadvantage of being non-renewable. Meanwhile, their CO₂ emissions have a significant impact on environmental issues such as global warming. Therefore, hydrogen production based on traditional fossil fuels cannot fit with the future industrial development trend. On the other hand, hydrogen produced via water electrolysis has purity as high as 99%, and the product, water, is environmentally friendly, which is in line with the current global trend of technological change. Moreover, renewable energy such as solar energy and wind energy can be combined in the hydrogen production process, achieving green hydrogen production with zero emission and pollution. The hydrogen production process can be completed; besides, it is conducive to the consumption and storage of renewable energy.

Electric energy is used to decompose water into hydrogen and oxygen in terms of the principle of hydrogen production via water electrolysis. Water electrolysis is classified by electrolyte into alkaline water electrolysis, proton exchange membrane water electrolysis with solid polymer (also known as proton exchange membrane (PEM) water electrolysis), anion exchange membrane water electrolysis with solid polymer (also known as anion exchange membrane (AEM) water electrolysis) and solid oxide electrolysis (SOEC). The four hydrogen production technologies have the same principle. Besides applied materials, the storage and operating conditions are also different [6].

The technology of hydrogen production via alkaline water electrolysis is quite mature. It is a low-temperature electrolysis technology, in which KOH and NaOH are used as solutions to generate hydrogen and oxygen under the action of direct current. Its efficiency can be up to 60%. However, the technology has problems such as long start-up time and poor adaptability. Therefore, it is more
appropriate for operation under stable voltage conditions and is not suitable for intermittent energy sources such as wind and solar energy.

PEM water electrolysis is a hydrogen production technology which developed from PEM fuel cell technology and catalyst technology. With a higher operating current density and fast start and stop, it is one of the most potential hydrogen production technologies recognized.

AEM water electrolysis and SOEC have not yet been commercialized though they have a high conversion rate. Therefore, they are both called new water electrolysis technologies. SOEC has an efficiency as high as 90% in the case of comprehensive waste heat utilization, but the technology is still in the research and development stage. In addition to SOEC, AEM water electrolysis technology combining the advantages of traditional alkaline liquid electrolyte water electrolysis and PEM water electrolysis has significant development potential in the future. The four methods of hydrogen production are organized as follows based on public data:

| Table 1: Comparison of water electrolysis technologies |
|--------------------------------------------------------|
| Items                        | Alkaline water electrolysis | PEM water electrolysis | AEM water electrolysis | SOEC |
| Electrolyte membrane         | 30% KOH and asbestos cloth  | PEM                    | AEM                    | Solid oxide |
| Current density              | <1A/cm²                    | 1~4A/cm²              | 1~2A/cm²              | 0.2~0.4A/cm² |
| Power consumption KWh/Nm³H₂ | 4.5-5.5                    | 4.0-5.0               | --                    | -- |
| Operating temperature        | ≤90℃                       | ≤80℃                  | ≤60℃                  | ≥80℃ |
| Hydrogen purity              | ≥99.8%                     | ≥99.9%                | ≥99.9%                | -- |
| Equipment volume             | 1                          | 约 1/3                | --                    | -- |
| Operating characteristics    | The pressure difference should be controlled. | Quick start and stop | Quick start and stop | Quick start and stop |
| Environmental protection     | The asbestos film is harmful. | Pollutant free       | --                    | -- |
| Degree of industrialization  | Fully industrialized       | Special application and initial stage of commercialization | Laboratory stage | Laboratory stage |

3.2 Hydrogen storage technology

Hydrogen storage technology is an intermediate link of hydrogen production and utilization in hydrogen fuel cells. Safety problems in large-scale hydrogen storage are hindering its development. The realization of large-scale, small-space and high-safety hydrogen storage is one of the key conditions for the rapid commercialization of new energy vehicles based on hydrogen fuel.

There are three technologies as below based on the state of hydrogen energy:

1) Gaseous hydrogen storage technology

Hydrogen energy exists in the gaseous phase under such technology. The technology can be classified by storage method into high-pressure gaseous storage and transportation technology and the technology of pipeline storage of hydrogen. The latter focuses on the transportation of hydrogen energy, so it cannot be applied to hydrogen fuel cells.

2) Low-temperature liquid hydrogen storage technology

The technology is applicable for long-distance and large-scale economic transportation of hydrogen energy, and is an important method of long-distance hydrogen transportation in China. It is only
suitable for engineering, national energy layout and other major aspects due to its problems about safety regulations to be settled urgently. It cannot be adopted for hydrogen storage in the application of hydrogen fuel cells.

3) Solid-state hydrogen storage technology

Hydrogen is stored through hydrogen-containing compounds and released from the solid-state compounds through reaction during use under the technology. The solid-state hydrogen storage with hydrogen storage materials as a medium is recognized as a promising hydrogen storage technology. The technology tends to be mature at present. Commercially viable hydrogen storage materials mainly include rare earth AB5, Ti-Fe AB, Ti-Mn AB2, Ti-V solid solution and magnesium hydrogen storage materials, etc.

The development of the technology is one of the key factors for the commercialization of hydrogen fuel cell vehicles. Its research and development focus on the high efficiency of hydrogen storage, process safety and material feasibility. The research and development of hydrogen storage materials are the core factor restricting the development of solid hydrogen storage.

Hydrogen carrier technology and composite hydrogen storage and transport technology have emerged with the rapid development of hydrogen energy. However, a new hydrogen storage technology still requires a long development and demonstration process due to the short development time.

3.3 Technology of fuel cells for vehicles

Fuel cells are different from traditional electric energy storage batteries. Their chemical energy is converted into electric energy through the fuel of internal materials. They have a high power generation efficiency. Most waste from power generation is safe and environmentally friendly. Meanwhile, only hydrogen and oxygen are consumed in hydrogen fuel cells. Therefore, hydrogen fuel cells have a broader market application prospect compared with traditional electric energy storage batteries. In fuel cell reactors, the addition and design of catalysts are undoubtedly the key factors to improve the performance of fuel cells. Considering environmental protection and other factors, commonly used catalyst products and key factors are organized as follows according to relevant data of enterprises:

| Indicators                        | SEC100       | SEC200       |
|-----------------------------------|--------------|--------------|
| Pt content (Wt%)                  | 20, 40, 60   | 10, 20       |
| Electrochemically active area     | 60–110       | 80–120       |
| (m²/gPt)                          |              |              |
| Mass activity (A/mg@0.9V)         | ≥0.2         | ≥0.4         |
| Endurance test (loss of mass activity) | ≤40%         | ≤40%         |

Among fuel cells, hydrogen fuel cells mainly include molten carbonate fuel cells (MCFCs), solid oxide fuel cells (SOFCs), polymer electrolyte fuel cells (PEFCs), phosphoric acid fuel cells (PAFCs). PEFC is the current research hotspot, which has the advantages such as low operating temperature and short start-up time.

4. Conclusion

The continuous "hydrogen heat" has facilitated the development of the global hydrogen fuel cell industry. Hydrogen fuel vehicles are now the focus and hotspot of research in the automotive field. Many companies around the world have designed and put into operation demonstration projects. The application of hydrogen fuel cells to large vehicles such as buses is also researched and developed besides their application to common household cars. Hydrogen fuel cell vehicles are gradually entering the stage of quality improvement in China according to the analysis of current conditions. In particular, they have developed rapidly in the past two years under the continuous stimulation of policies, but problems still exist in key links, such as incomplete hydrogen storage materials, low
feasibility of commercialization and insufficient hydrogen refueling stations. With the rapid development of hydrogen energy, the hydrogen fuel cell vehicle industry will usher in a period of rapid growth with significant economic and social benefits.

Acknowledgments
This paper is one of the phased achievements of the research project titled Education and Teaching Reform & Innovation and Practice of Teachers in the Professional Field of Photovoltaic Power Generation Technology and Application in Higher Vocational Colleges in the New Era (03005401) carried out by a national vocational education team.

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