Safety Technologies and Challenges of Hydrogen-Powered Rail Transport

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Abstract. As one of the many energy alternatives, the interest in hydrogen-powered rail transport is gradually increasing worldwide, and some railway vehicles powered by hydrogen are currently in operation or undergoing experimental projects. However, due to the unsafe and unstable nature of hydrogen energy, hydrogen has potential leakage and explosion hazards in all rail transport applications. This paper summarizes the main application technologies of hydrogen safety in light of the research progress and unsafe factors in the process in the field of hydrogen-powered rail transport in various countries, at the same time clarifies the development challenges and difficulties of hydrogen-powered rail transport in the future, and makes suggestions for the development of hydrogen-powered rail transport safety in China.

Keywords: Hydrogen-powered rail transport risk · Hydrogen safety technology · Hydrogen-powered rail transport challenges

1 Introduction

After the signing of the Paris Agreement in 2016, countries all over the world have started looking for a new type of energy that can replace traditional fossil fuels. Hydrogen energy is gradually favored by countries for its advantages of zero carbon emission, non-toxicity and high energy density. With the maturity of the technology, hydrogen energy is developing rapidly and gradually applied to passenger cars, subways and trams, becoming an important part of the urban transportation network. In the rail transport industry, hydrogen-powered vehicles are involved with the operation of hydrogen refueling, hydrogen storage and hydrogen reaction, which may lead to accidents such as hydrogen leakage and explosion. That raises more requirements on the engineering process and the safety measures. Therefore, how to apply hydrogen energy safely, stably and efficiently in the rail transport industry has become a key and difficult point for all countries today.

2 The Exploration of Hydrogen-Powered Rail Transport

More than 10 countries are implementing or planning to implement hydrogen-powered rail vehicles to date [1] and the first delivery peak of hydrogen-powered rail vehicles is expected to be in 2025.

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The U.S. signed a related agreement in 2020 and expects to deliver the country's first commercial hydrogen-powered passenger train (Flirt H2) in 2023 and officially put it into service in 2024. The Korea Railway Research Institute announced on April 20, 2021 that it is researching on a 150 km/h liquid hydrogen-powered train with a maximum range expected to be 1.6 times that of the 700 bar gaseous hydrogen-powered trains. And the time required to refill with liquid hydrogen is expected to be 20% less than gaseous hydrogen, and the research is expected to continue until 2025. Germany was the first country in the world to put hydrogen-powered trains into commercial use, and has worked with Alstom on hydrogen fuel cell trains several times in recent years, with the first fleet of 14 iLINTs going into regular operation in Germany by the end of 2022. The first hydrogen-powered test train of Japan, the Hybari, was jointly developed by JR East, Hitachi Ltd. Toyota Motor Corp and unveiled in 2022. The train is scheduled to enter service in 2030 (Figs. 1 and 2).

Fig. 1. Flirt H_2 hydrogen fuel cell train

Fig. 2. Japanese "Hybari" train

By the end of 2022, the first hydrogen-powered locomotive jointly developed by Southwest Jiaotong University and CRRC Datong has exceeded 20,000 kilometers of safe operation, saving about 110 tons of fuel consumption and reducing carbon emissions by about 350 tons. In Guangdong, Foshan Gaoming tram, the first hydrogen -powered railway system in China has been operated commercially since 2019, and the train can travel 100 km when fully filled with hydrogen. The first hydrogen-powered regional express vehicle in the world was released by the end of 2022, which can achieve a long range of 600 km (Figs. 3 and 4).

Fig. 3. The first hydrogen-powered locomotive

Fig. 4. The world's first hydrogen-powered regional express vehicle

3 Safety Risks of Hydrogen in Rail Transport

3.1 Failure of On-board Hydrogen Energy Devices

For on-board hydrogen storage, hydrogen needs to be compressed, liquefied or materially combined to achieve higher energy density [2]. Compared to conventional diesel, hydrogen shows significantly lower volumetric and mass energy density at the storage system level, which severely limits the operation distance as well as the refueling process of the vehicle. During the refueling process, the rapid filling of hydrogen can lead to a rapid temperature increase in the hydrogen storage tank, and since the lateral stretching of the hydrogen storage tank can be significantly affected by temperature changes, the tank may fail under excessive pressure, thus triggering hydrogen leakage. Hydrogen storage tanks are also susceptible to accidents caused by human handling, material problems, etc. When hydrogen storage tanks are mixed with other gases, there is a risk of explosion due to dangerous chemical reactions under certain conditions. At the same time, hydrogen storage tanks have to face the problem of compatibility between hydrogen and its materials [3]. The phenomenon of "hydrogen embrittlement" threatens the material safety of certain equipment working in hydrogen environment for a long time, and the deterioration of metallic materials can be a serious threat to the safety of hydrogen systems.

3.2 Lack of Safety Regulations for Hydrogen Vehicles

There are no applicable regulations and standards for on-board hydrogen storage of rail transport. Although most hazardous accidents can be controlled by combining existing regulations in other hydrogen applications with existing rail-specific standards, the hydrogen technology standardization system of China suffers from a low number of industry standards, weak dominance of hydrogen industry consortia in industry standard development, and low coverage of some technology categories [3]. An acceptable level of residual risk must be reached to solve the residual risk. China has not yet formed a comprehensive risk evaluation system for hydrogen energy systems and mastered the identification method of major hazards related to hydrogen energy infrastructure in the field of hydrogen-powered rail transport, and at the same time has not established effective measures to deal with hydrogen-powered vehicle accidents and emergency safety response mechanisms [4].

In terms of the quality of hydrogen vehicle-related components, China's hydrogen safety quality evaluation system still needs to be improved, and there is still a lack of authoritative and commonly recognized third-party hydrogen safety testing and research center. At the same time, the capacity of safety testing, measurement and certification of relevant departments needs to be improved.

3.3 Inadequate Hydrogen Fire Prevention and Control Technology in Tunnels

Generally speaking, most of the hydrogen storage systems of railway vehicles are installed on the roof or in the engine room, and once the hydrogen fuel cell leaks in the open space, the released hydrogen gas will quickly dissipate upward by virtue of its small density and strong diffusivity, and cannot accumulate. However, in such a narrow and restricted space as tunnel, hydrogen gas is very easy to accumulate above the train, and due to the dangerous nature of hydrogen gas such as low ignition energy, flammable and explosive, the accumulation of hydrogen gas is more likely to cause combustion to form a jet fire or explosion. At the same time, the wind speed and direction inside the tunnel as well as the location of hydrogen leakage inside the tunnel also affect the diffusion process of hydrogen leakage [5].

In the event of a hydrogen ignition in a tunnel, the formation of a jet fire can quickly pyrolyze the surface materials or parts of the train, spreading smoke and flames through the cars and tunnel, resulting in reduced visibility, difficult evacuation, and even fatal poisoning of personnel. In addition to the ventilation conditions, the flammability and thermal response time of the interior materials and the mass of combustible materials, which are the main factors affecting the heat release rate of a train, the geometry of the tunnel entrance can also have an impact [6].

4 Hydrogen-Powered Rail Transport Safety Technology

4.1 On-board Hydrogen Safety Technology

Many researches have conducted to reduce the safety risks associated with the operation of hydrogen-powered vehicles in different aspects. Hydrail has made significant progress in passenger rail by deploying a highly visible demonstration system to monitor the real-time status of fuel cells. China Railway Siyuan Survey and Design Group Co., Ltd. Has released a hydrogen-powered tram hydrogen power system temperature monitoring device [7], which will cool down and extinguish fire when abnormal temperature or open flame source is monitored and alarm occurs simultaneously, thus solving the problem of hydrogen-powered tram power system temperature rise and spark generation, which threatens the safety of hydrogen power system. For the problem of hydrogen leakage when the hydrogen-powered trams are parked in the depot, the hydrogen leakage monitoring and elimination system of hydrogen-powered tram depot [8] can automatically turn on the exhaust fan to discharge the hydrogen out of the depot, thus saving time for emergency treatment and greatly reducing the possibility of danger. Qingdao CRRC Sifang Rolling Stock Co., Ltd. Has invented a rail vehicle hydrogen energy equipment installation device [9], which enables the ready assembly and disassembly of facilities and equipment through modular design, and at the same time can be adjusted in size according to hydrogen energy equipment or similar products to meet the needs of different specifications of products, and uses cylindrical pressure cylinders to reduce the storage capacity under consideration of additional installation space such as pipes and shells.

4.2 Related Hydrogen Safety Standards

In recent years, the government of China has paid more attention to renewable energy, which aims to ensure safe production and application, and encourages all parties to pay attention to the production, storage and transportation processes and firefighting needs of hydrogen-powered vehicles. In terms of hydrogen refueling process and safety management of hydrogen-powered vehicles, temporary hydrogen refueling equipment configuration, temporary hydrogen refueling process, safety measures for hydrogen refueling operation and emergency treatment plan for hydrogen trains have been focused and effectively discussed [10], which provides partial reference for the hydrogen energy industry. Regional quantitative risk evaluation software is also gradually developed and recognized by many domestic safety evaluation agencies, gradually realizing that safety of hydrogen-powered vehicles can be measured, prevented and followed. Zhang Feng et al. [11] put forward requirements for hydrogen-related area management, hydrogen storage module safety design of trams and hydrogen storage module maintenance requirements in the safety design and maintenance management of hydrogen—powered trams, and elaborated the application practice of hydrogen-related component overhaul and maintenance of hydrogen energy trams, which provides action guidelines for subsequent operation and management. At present, relevant safety technical specification documents of hydrogen refueling stations have been released, in which further requirements are unified for technical requirements of hydrogen storage pressure vessel, safety assurance during transportation and hydrogen risk identification.

4.3 Tunnel Hydrogen Explosion Prevention and Control

The researchers analyzed the consequences and causes of railway tunnel fire safety accidents around the world by establishing relevant mathematical and physical models [12–18], studied the development of railway tunnel fire laws in more depth, and proposed numerous measures to help reduce railway tunnel fire safety accidents and reduce the scale of train fires in tunnels, in order to further improve the level of safety operation inside railway tunnels and ensure the smooth operation of hydrogen-powered vehicles after entering the tunnels. These include the application of flame retardant technology, the use of partially non-combustible materials on the surface of the train, strict control of the size of the natural wind speed in the tunnel, the lowest possible number of open train doors and windows when meeting the requirements for personnel escape, and ensuring that the spacing between firefighting facilities in the tunnel meets the standards. In recent years, with the development of the Internet of Things, domestic and international institutions are currently developing an integrated information platform for fire safety and disaster mitigation and relief in tunnels [6], which mainly covers fire prediction and alarm system, tunnel fire intelligent consultation system, fire management system and safety emergency response system, etc. Under the normal working environment, each system automatically adjusts its working status through dynamic monitoring and real-time monitoring, etc. The system is designed to meet the requirements of tunnel fire safety and disaster mitigation and relief in a modern, informative and intelligent way [19, 20].

5 China's Hydrogen-Powered Rail Transport Challenges

5.1 On-board Hydrogen Device Research Needs to be More In-depth

Several challenges remain in using hydrogen fuel cells to power railway vehicles, and the safety of the hydrogen storage tank determines the level of risk for hydrogen-powered vehicles and becomes the basis for achieving smooth operation of hydrogen trains. Although it is technically possible to reduce the storage space required for hydrogen by compressing the hydrogen to high pressure, however, the mechanisms of hydrogen spontaneous combustion, flame acceleration and ignition-detonation transition are still unclear, there is a lack of test data on materials under the operating environment of hydrogen-powered vehicles over a long period of time, and the validity and applicability of risk assessment models still need to be further tested, all of which are technical challenges limiting the rapid development of hydrogen-powered rail transport.

5.2 Hydrogen Safety Regulations Need to be Improved

The technical standards and safety regulations related to hydrogen energy are not yet perfected and unified. According to statistics, the number of hydrogen energy-related standards in China is more than the sum of European, American and Japanese hydrogen energy standards, but they fail to effectively support industrial development, and there is still a cross-regional information gap.

5.3 Hydrogen Rail Accident Rescue Technology Still Needs to be Improved

Although numerous analytical studies have been conducted previously to evaluate the operational risk of vehicles in special transportation scenarios such as tunnels, ports and high altitude areas, there is still a lack of data and experience in the field of hydrogen-powered rail transport to quantify the risk, and it is difficult to summarize the specific laws for the possible fire hazards. For different types of vehicles entering the tunnel, the level of tunnel operation management in China needs to be improved, and the emergency rescue countermeasures corresponding to the safety level of fire prevention in the tunnel still need to be unified.

6 Conclusion

Hydrogen energy is regarded as the second most important secondary energy source after electricity in the future by many countries, and it will occupy a large proportion in the transportation field. In the future, China still needs to strengthen the research on the safety technology of hydrogen energy infrastructure equipment operation, improve the accuracy of relevant risk assessment methods, accurately identify the major sources of danger in the abnormal operation of hydrogen-powered rail vehicles, form a mature risk response system for special transportation scenarios, and establish a rapid response mechanism. At the same time, we should further improve the hydrogen safety quality system in China, set up a professional research center for hydrogen equipment, strictly control all the industry chains involved with the domestic production and import and export of hydrogen equipment, accelerate the development of relevant standards, and form a standard on which the hydrogen-powered rail industry chain can jointly rely.

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