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The Development Status and Prospect of Hydrogen Fuel Cell Powered Tram

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Abstract. The problem of energy and environmental pollution is a huge challenge for the development of contemporary society. Hydrogen energy has emerged as a prominent area of current research to address this issue. Researchers have found that applying hydrogen fuel cells to trams can solve the problem, but the feasibility of this technology has yet to be analyzed. Herein, this paper explores the power system and commercial feasibility of hydrogen-fueled trams regarding their technical issues, security assessment, and cost estimation. It is found that compared with traditional trams, hydrogen energy trams have the advantages of high energy utilization and long driving range and achieve zero emission in the operation process. At the same time, with the continuous development of technology, issues related to the safety of hydrogen use will be verified, and the cost will be further reduced with the development of low-platinum fuel cell catalysts and Type IV hydrogen storage tanks. The feasibility of hydrogen-fueled trams has been confirmed as multiple trains have rolled off the assembly line, and with the determination of relevant industry norms, it will definitely be widely used.

1 Introduction

In the wake of societal advancement in the 21st century, the issues regarding energy and environmental pollution have presented significant challenges to the progress of conventional internal combustion engine vehicles. Consequently, the imperative for research and development of new energy vehicles has intensified. With its capacity for clean utilization and abundant sources, hydrogen energy has garnered considerable attention, fostering its notable development. Therefore, hydrogen-powered fuel cell vehicles have become a hot spot in current automotive technology research. Hydrogen energy possesses notable merits, such as extended driving range, robust overload capacity, enhanced efficiency, and reduced noise levels. Furthermore, the water produced as a byproduct of the electrochemical reaction between hydrogen and oxygen enables the attainment of a genuinely pollution-free environment, facilitating zero emissions. Consequently, these characteristics align closely with China's commitment to implementing the "carbon neutral" strategy. Therefore, the development prospect of hydrogen fuel cells is promising. Nevertheless, the development time of hydrogen energy trams is short, the research is not sufficient, and the battery life and safety need to be verified over time. Further, the issue of the higher cost compared to traditional trams cannot be ignored, and the route design of hydrogen energy trams depends on the layout of hydrogen refueling stations. However, there is no complete set of standards and procedures for the construction approval of hydrogen refueling stations in China. To sum up, the development of hydrogen energy in China is still in the initial stage, and there is a long way to go.

This study compares trams with traditional powertrains and hydrogen fuel cell systems. Modern trams run solely on overhead catenary or onboard energy storage; not only does it have a bad impact on the beauty of the city, but its traditional power battery capacity cannot meet its work needs. Therefore, it is increasingly important to find a new type of power system to replace the traditional one. This study initiates by conducting a comparative and analytical assessment of the power system architectures employed in traditional trams and hydrogen energy trams. Subsequently, a safety analysis is performed, focusing on the airtightness and insulation aspects of hydrogen fuel cells. Furthermore, the paper investigates and discusses strategies to mitigate the costs associated with platinum metal and hydrogen storage tanks within the proton exchange membrane fuel cell's membrane electrode.

2 Comparison between traditional tram and hydrogen fuel powered tram

The tram has been manufactured for the first time since 1881 and has developed for hundreds of years. Because it is driven by electricity and does not discharge exhaust gas, it has been vigorously developed in recent years. Mainland China opened a tram for the first time in Tianjin in 1906. According to the "Urban Rail Transit 2021 Annual Statistics and Analysis Report" released by the China Municipal Rail Transit Association on April 22, 2022, as of the end of 2021, the total length of trains in Mainland China reached 503.6 kilometers [1]. Therefore, efficiency and energy cost become key issues for developing trams. Today, the main power supply methods of modern trams can be divided into vehicle energy storage power supply, set-up contact network power supply and vehicle energy storage and contact

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network power supply [2]. However, the overhead contact network power supply and vehicle energy storage power supply have an adverse impact on the beauty of the city. At the same time, because some lines are long, the current capacity of traditional power batteries cannot meet their work needs. Supercapacitors are most widely used in energy storage power supply equipment, and it has run on multiple domestic routes. However, with the development of new technologies, hydrogen energy batteries have begun to be applied to rail transit systems, and their battery life can reach about 20 times the supercapacitor. Therefore, the application of hydrogen fuel cells will bring a revolution in energy.

2.1 Traditional tram with super capacitance as the main energy storage element

Supercapacitors, also known as dual-electro-compatible capacitors, are a new type of energy storage component that gradually developed in the middle of the last century. Because it only occurs in the process of discharge storage, the supercapacitor has a longer service life and higher efficiency compared to traditional batteries. At the same time, supercapacitor also has the characteristics of fast charging and discharge, which can better meet the characteristics of frequent startup trams and short charging time. The structure of the supercapacitor power supply system is shown in Figure 1.

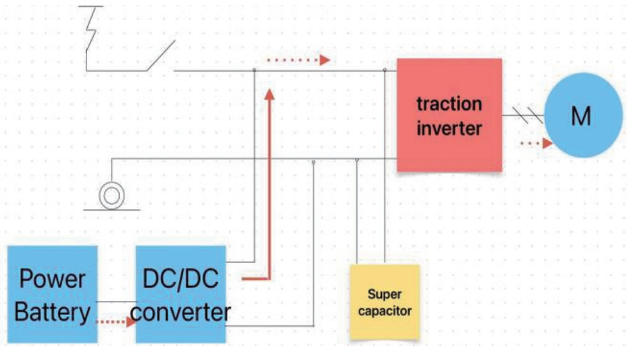

Fig. 1. Super Capacitor Power Supply System Structure Drawing（Picture Original）

However, because the energy density of the supercapacitor is low, and the space occupies a large space, which leads to a short range of mileage, supercapacitors are not the optimal solution to the motor of the tram.

2.2 The new type of tram with hydrogen fuel cells as power

Hydrogen energy rail trams use hydrogen fuel cells as power sources, and it has no contact network, substation and other systems on the entire line, which not only solves the problem of conventional trams that need to set up a contact network but also solves the bottleneck of the short range of ordinary energy storage trams[3]. Due to the launch and frequent driving characteristics of rail trams, the power changes required by the traction system during the operation are fierce. However, the response to the need for transient power for fuel cells is relatively slow. Therefore, in the power supply process, the fuel cell is powered by relatively stable power as the system to power the system, and the energy storage system can meet the instantaneous power requirements. Therefore, the hydrogen fuel cell rail tram power supply system should be an electric-electric hybrid power supply system containing fuel cells and energy storage systems, with a small part having supercapacitors [4]. At present, the power of hydrogen energy trains can be divided into two types:1. Burning hydrogen to generate power to promote the train; 2. Hydrogen fuel cell + electric motor combination, where after the hydrogen or hydrogen-containing substances and the oxygen in the air react in fuel cells to generate electrical energy, the motor drives the train by the motor [5].

On March 19, the world's first hydrogen energy rail trams were completed and offline in the southern cars. The car is another major innovative achievement of Southern Cycling in trams after the permanent Magnet Modern tram and mixed energy storage tram. Its adventure fills the gap in the application of hydrogen energy in the global tram field and also makes China the first country in the world to master the hydrogen energy rail tram technology [6].

This article takes the Gaoming Corridor tram opened in 2019 as an example to introduce the characteristics of the tram of hydrogen fuel cells. Hydrogen energy rail trams are powered by a hydrogen power system and lithium titanate batteries. The hydrogen power system mainly includes a fuel cell system, hydrogen storage subsystem, cooling subsystem, DC-DC power device, power battery and fuel cell energy control system. The hydrogen storage subsystem supplies hydrogen for fuel cells, including injection, storage and supply of hydrogen. At present, the hydrogen energy tram hydrogen storage system is equipped with 6 hydrogen storage cylinders， its rated work pressure is 35 mPa, and the volume of the rated charge is 840 L. After it is full, it stores a total of 20 kg of hydrogen, and its range can reach 80 ～ 100 km[7].

The Gaoming tram power system is composed of hydrogen fuel cells and power batteries. Based on the actual requirements of the train operation, when the train starts and accelerates, the power battery provides instantaneous high power to meet its needs. And hydrogen fuel cells provide stable output during smooth driving, while also charging the power battery. This not only meets the power needs of the train at a specific time but also gives full play to the output characteristics of the two batteries. The train power system is shown in Figure 2.

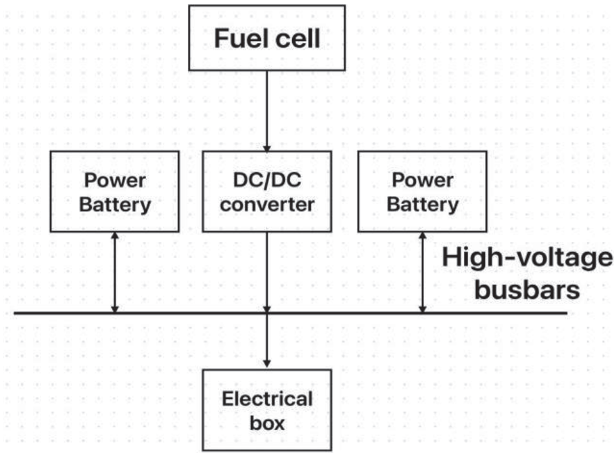

Fig. 2. Simple diagram of hydrogen energy power tram power system（Picture Original）

Among them, the DC/DC unit is a boosting device for the power system to convert the low voltage output from the fuel cell into the rated output voltage of the 750V tram 750V and also charge the battery.

Hydrogen energy trams can run for 100 km with hydrogen filling once, and the endurance time is 4 ~ 5 h. Due to the restrictions on endurance, the arrangement of this line operation plan is different from the conventional practice. It is also necessary to consider the matching of the hydrogenation plan. For instance, six operating trains (I-6 trains) are grouped for hydrogen refueling, which matches the full-day driving plan [3].

2.3 Comparison of two types of trams

According to the characteristics of the tram, in addition to ensuring the safety and reliability of the power supply medium of trains, it should also have characteristics such as high energy density, high power density, long life, strong environmental adaptability, fast and convenient charging and convenient charging, etc.[8]. As shown in Table 1, compared with supercapacitors and hydrogen energy, both have advantages and disadvantages.

Table 1. The technical indicators of supercapacitor and Gaoming hydrogen energy[9]

Main technical performance	Supercapacitor	Hydrogen energy battery（Take Gaoming Rail as an example）
Battery principle	Polarized electrolyte	Chemical reactions, proton exchange
Power density ($W \cdot kg^{-1}$)	300～5000	52
Energy density ($W \cdot h \cdot kg^{-1}$)	5	260
Energy/energy utilization	>95%	about45%
Charging/hydrogenation time	Very short (generally 30s)	15～30 min
Cruising range/km	4～5	about 100

It can be seen that the energy density of hydrogen energy fuel cells is much greater than super capacitance, and its mileage is also about 20 times that of traditional supercapacitor. However, it is not as good as traditional supercapacitors in power density, energy utilization and charging time.

3 Feasibility of hydrogen fuel cell trams

3.1 Security Performance Analysis

Hydrogen is lighter than air, leakage from a hydrogen storage tank will spread rapidly, and the diffusion coefficient of hydrogen in an open space is 12 times that of gasoline, and the flash point temperature of hydrogen is about 500 °C, compared with the flash point temperature of gasoline -50 °C～-20 °C, the possibility of spontaneous hydrogen ignition is very low. However, in recent years, there have been many accidents, such as hydrogen leakage and explosions. On May 23, 2019, a hydrogen storage tank with a capacity of 400L exploded in Daejeon-dong Science and Technology Park, Gangneung City, Gangwon-do, South Korea, killing 2 people and injuring 6 people [10]; On June 1, 2019, Air Products' hydrogen trailer transportation facility in Santa Clara, California, USA, experienced a large-scale uncontrolled release of high-pressure hydrogen gas during the gaseous hydrogen filling process of a modular multi-tank trailer, and an explosion occurred [11]. The occurrence of these accidents warns everyone that sufficient safety research should be carried out before the large-scale application of hydrogen energy.

3.1.1 Air tightness experiment of hydrogen fuel cell system

Since hydrogen is flammable and explosive, and the flammable range is 4-75Vol%, the explosive range is 18-59Vol%, colorless and odorless, Hydrogen leaks fail to alert people's senses. Therefore, one of the important performances related to the safety of the hydrogen fuel cell system is the airtightness of the battery. The comparative analysis of the specific air tightness test is shown in Table 2.

For the GB/T 25319—2010 standard, the air tightness is tested by passing the inert gas into the stack, keeping the pressure (not exceeding the allowable pressure) and stabilizing it for 60s, then measuring the leakage gas flow. While for the ISO 12619-2—2014 standard, it is necessary to first purge the stack with nitrogen, use hydrogen for testing, and test the stack at a specified pressure. Regarding the GB/T 24554—2009 standard, the testing procedure is as follows: Use inert gas to enter the stack, and keep the pressure at 50kPa; after the pressure is stable, keep it for 20min, and then measure the pressure drop value. Finally, for the T/CSAE 123—2019 standard, it is required to detect the hydrogen airtightness and emission safety of the vehicle under high temperature, idling speed, air conditioner on and frequent start and stop.

Analysis of the above table shows that the test method with the standard number T/CSAE 123-2019 is

Table 2. Air tightness test comparison [12]

Standard	GB/T 25319—2010	ISO 12619-2—2014	GB/T 24554—2009	T/CSAE 123—2019
test gas	inert gas	hydrogen	inert gas	hydrogen
air tight-ness index	manufacturer's specification	Under specified conditions less than 10Ncm3/h	The pressure drop value complies with the regulations	After 8 hours, the volume concentration of hydrogen is not more than 1%
Pros and Cons	Simple and easy, poor consistency	standardized experimental conditions, complicated process	Unrestricted experimental conditions	Develop specific experimental methods for each operating state

more suitable for hydrogen-fueled trams. However, more specific experimental methods should be developed according to different fuel cell operating states. As public transportation, the safety requirements of trams should be higher. Therefore, the real driving environment should be simulated as much as possible during the test, and it is also necessary to conduct contingency research on various possible emergencies to ensure the smooth operation of trams and the safety of passengers.

3.1.2 Insulation experiment of hydrogen fuel cell system

The insulation of fuel cells is related to the safety of users and passengers. According to the analysis of the international comparison of insulation experiments of fuel cell systems, the insulation performance comparison is shown in Table 3.

Through comparison, it can be found that the standard requirement value of insulation resistance specified in GB/T 25319-2010 is lower than that of ISO 12619-2-2014, And ISO 12619-2-2014 stipulates that the power supply wire and the component shell need to be energized at 1000V DC for at least 2S.

Table 3. Comparison of insulation experiments [12]

GB/T 25319—2010	ISO 12619-2—2014	ISO 12619-1—2014
The insulation resistance of the positive and negative electrodes to the vehicle body should be greater than 100Ω/V	Apply 1000V direct current between the power wire and the component casing for at least 2 seconds, and the allowable resistance of the component should be 240 k Ω	Construction and assembly of specified materials, installation and wiring of electrical equipment

3.2 The cost of hydrogen fuel cells

Proton Exchange Membrane Fuel Cell (PEMFC), The principle of PEMFC is equivalent to the "inverse" device of water electrolysis, which is a chemical device that directly converts the chemical energy of hydrogen and oxygen into electrical energy. PEMFC supplies hydrogen and oxygen to the anode and cathode, respectively, after hydrogen diffuses outward through the anode and reacts with the electrolyte, The discharge electrons then reach the cathode through an external load [13]. The electrode of the fuel cell is composed of a gas diffusion layer and a catalyst layer. The catalyst layer provides a place for electrochemical reactions and speeds up the rate of chemical reactions inside the battery [13]. At present, there is much research carried out on surpassing or replacing Pt electrodes or making Pt into metal nanoparticles. However, there is no particularly outstanding operational stability and industrial expansion performance. But fortunately, breakthroughs and progress have been made in low-platinum fuel cell catalysts. Breitwieser et al. [14] fabricated a kind of platinum catalyst polymer eectrolyte membrane fuel cells with high utilization efficiency by direct membrane deposition. In Figure 3, it is observed that at a temperature of 80 °C and pressure of 300 kPa, the catalyst demonstrates an exceptionally low loading of 0.029 mg·cm^{-2}. Under these conditions, the hydrogen-oxygen fuel cell exhibits an impressive power output of 2.56 W·cm^{-2}. Remarkably, the platinum utilization rate reaches an exceptional value of 88 kW·g^{-1}, representing the highest utilization rate achieved thus far. Comparative analysis with advanced catalyst-coated membrane (CCM) fuel cells reveals that the film thickness measures between 8-15 μm, which is smaller than the commercial N-211 variant (25 μm). Additionally, this reduced thickness contributes to a significant decrease in ionic resistance and leads to an increase in power density within the high current density range [15]. Therefore, it is believed that the cost of hydrogen fuel cells will be further reduced shortly, which will bring good development prospects for hydrogen fuel cell trams.

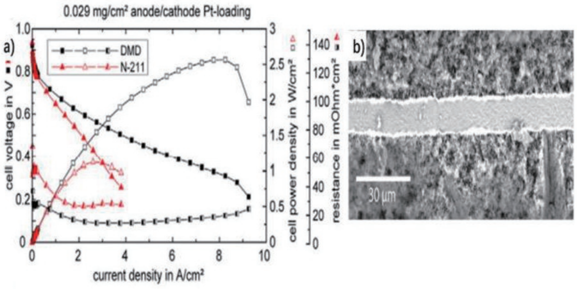

Figure 3. (a) Membrane electrodes prepared by direct film deposition method and traditional CCM method under the ultra-low load of 0.029mg • cm^{-2} for cathode and anode, hydrogen-oxygen fuel cell test chart; (b) Scanning electron microscope image of membrane electrode cross-section prepared by direct deposition of the film [16]

3.3 Hydrogen-fueled tram hydrogen storage tank cost

The design, maintenance and maintenance of onboard hydrogen storage tanks are one of the important expenditure items of vehicle use costs. Hydrogen storage technologies currently used or under research include high-pressure gaseous hydrogen storage, low-temperature liquid hydrogen storage, activated carbon low-temperature adsorption hydrogen storage, liquid organic hydride hydrogen storage, solid-state hydrogen storage, etc. Since the application in trams will be limited by volume and mass, the main technical indicators of the onboard hydrogen storage system are the hydrogen storage density per unit mass and the hydrogen storage density by volume. So far, the mass hydrogen storage density of the onboard 35Mpa hydrogen storage tank is 3%, reaching 4.5% at 70Mpa, and the unit hydrogen storage density is high [16]. Therefore, comprehensively considering the ideal storage pressure of high-pressure hydrogen is 35Mpa ~ 70Mpa. Currently, the type III 35Mp hydrogen storage bottle is mainly used in China, and now a type III 75Mpa hydrogen storage bottle has been developed, with a hydrogen storage density of 3.9%, which is more suitable for those with sufficient installation space but no high mileage requirements. Compared with the Type III hydrogen storage bottle, The type IV hydrogen storage bottle is changed from a metal liner to a plastic liner made of fully wound carbon fibers, which makes it less prone to fatigue failure and greatly improves service life. Carbon fiber composites are 6 times stronger and 4 times stiffer than steel, less likely to deform after being hit, lightweight and suitable for vehicles that are limited by installation space but have high requirements for cruising range. According to estimates, the cost of a 35MPa type IV hydrogen storage bottle is about 15% higher than that of a 35MPa type III bottle; however, the cost of a 70MPa type IV hydrogen storage bottle is about 30% lower than that of a 70MPa type III bottle [17]. Therefore, with the development of type IV bottles, the market demand will increase, and the cost of materials will be further reduced. According to the calculation of the American Automotive Research Council, when the production scale of gas cylinders increases from 10,000 sets to 500,000 sets, the cost of hydrogen cylinders will drop by 20%. When applied to hydrogen-fuelled trams, it can reduce the number of hydrogen refills, the construction of hydrogen refuelling stations, and the cost of using vehicles.

4 Conclusion

The burning product of hydrogen is water and does not bring environmental pollution. Due to its rich sources, high thermal value, and high efficiency, global governments have increased the development of hydrogen energy and its application in transportation research. Hydrogen fuel cells have achieved breakthrough results and hold a certain share of today's market. Hydrogen fuel cells have longer battery life compared to supercapacitors, but they still need to be improved in terms of hydrogenation speed and energy utilization. The hydrogen fuel cell system occupies the main position in its related industrial chain, while safety and service life performance has always been the leading problems. The gas tightness and insulation experiments of hydrogen energy batteries can simulate the real driving environment for solving related safety problems, essential in guaranteeing the large-scale application of hydrogen energy rail trams. In addition, realizing its commercialization needs to solve the cost problem. Currently, PEMFC accounts for the main position, and the price of catalyst pt directly affects the cost of the battery. Fortunately, low platinum fuel cell catalysts have achieved significant breakthroughs and progress. Finally, the design and maintenance of hydrogen storage tanks are an important part of the tram use process. With the development of IV hydrogen storage tanks and the formation of marketization, cost issues will be resolved. Recently, many hydrogen-powered trains have been offline in China. It has greater advantages over traditional energy power, and its feasibility is verified, but the shortcomings still exist. The standards and specifications of the industry have not been determined, and cost, transportation and safety issues are still the resistance to large-scale applications. With the continuous improvement of facilities and technologies in related fields and the strong support of the government, the application of hydrogen fuel cell trams will become wider and wider, and it will definitely bring an energy revolution.

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