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Comparison of Hybrid Vehicle Technology and Hydrogen Fuel Cell Engine Technology

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Abstract. As a new automotive technology, hydrogen fuel cell engines still have many differences compared to traditional hybrid technologies. This article studies the core comparison between the two technologies, starting with an introduction to the evolution of automotive engines, and then introducing the components, technical characteristics, and working principles of hybrid vehicles and hydrogen fuel cell vehicles, comparing the quantitative performance of the two using data, and listing qualitative advantages. The study will discuss the current problems of both and provide corresponding improvement suggestions based on references, and reflect on the future development trends of both through references. Research has shown that hybrid vehicles are currently the optimal choice, while hydrogen fuel cell vehicles are a long-term solution to achieve decarbonization goals. While comparing the two types of technologies, this article will also evaluate their roles in sustainable development. This article aims to provide a more comprehensive perspective to help people better understand hybrid technology and hydrogen fuel cell technology, as well as their impact on today's automotive industry.

Keywords: Traditional hybrid technology, hydrogen fuel cell technology, sustainable development, future trends

1. Introduction

With the increasing global demand for sustainable energy and clean technology, the evolution of automotive engine technology has become an issue that cannot be ignored.

The fundamental deficiency of traditional hybrid technology is still its dependence on fossil fuels, which can emit harmful gases. However, the advantage of hydrogen fuel cell technology is that it relies solely on chemical reactions to drive vehicles and does not emit harmful gases. In addition, hydrogen fuel cell technology has advantages such as stronger environmental adaptability and a better driving and riding experience. However, this emerging technology faces challenges and gaps, such as safety risks posed by hydrogen properties, gaps in unified safety standards, and increased overall costs due to scarce infrastructure.

The purpose of this article is to compare the differences between traditional hybrid technology and hydrogen fuel cell technology in terms of environmental impact, energy conversion efficiency, and development level, and to discuss existing problems and corresponding improvements. This article aims to analyze and compare two technologies to help people better understand hybrid

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technology and hydrogen fuel cell technology, and provide reference for the technological development of the automotive industry.

2. The historical development and evolution of automotive engine technology

The origin of automobile engines can be traced back to the 18th century, when the earliest cars were driven by steam. In 1876, the birth of the Otto engine marked the birth of the core principle of modern gasoline engines with a four-stroke cycle of "intake-compression-work-exhaust". In 1885, Karl Benz invented the first modern three-wheeled car with a single-cylinder gasoline engine. After the end of World War II, environmental requirements and the energy crisis forced the transformation and upgrading of engine technology, and engines officially entered the electronic control era from the pure mechanical era. In the late 20th century, electronic fuel injection technology gradually replaced traditional carburetors, relying on on-board computers to accurately control fuel supply, reducing fuel consumption and exhaust pollution effectively. At the same time, the popularization of technologies such as variable valves, turbocharging, and three-way catalysts has enabled engines to balance power performance and environmental standards, adapting to increasingly stringent travel requirements.

Since the 21st century, engine technology has been developing towards high efficiency, miniaturization, and electrification. Direct injection and small displacement turbocharging technologies have become mainstream, achieving a balance between power and energy consumption. Hybrid electric vehicles, with the form of "internal combustion engine + electric motor coupling", enable the engine to operate in a high-efficiency range for a long time. The internal combustion engine no longer drives the entire vehicle alone, and the engine begins to compromise and optimize for electrification. With the rapid development of new energy technology, power battery technology is gradually maturing, pure electric vehicles are gradually becoming popular, and traditional internal combustion engines are gradually shrinking their production capacity. At the same time, energy efficiency limits of internal combustion engines are constantly being explored to adapt to the environmental and energy-saving requirements of the new era.

3. Comparison of traditional hybrid technology and hydrogen fuel cell technology core

3.1. The structural composition of hybrid vehicles

Hybrid technology refers to a technology that uses two different power sources in the vehicle power system, with a greater emphasis on hybrid electric vehicles. The emergence of hybrid technology is due to the improvement and optimization of traditional vehicle power systems. The entire hybrid power system includes a fuel power subsystem, an electric drive subsystem, an electromechanical coupling device, an electronic control management subsystem, and auxiliary ancillary systems.

Hybrid engines often use the Atkinson/Miller cycle and low-pressure exhaust gas recirculation technology, and are matched with fuel tanks, fuel supply pipelines, and exhaust systems. As a basic power source, Hybrid engines can independently drive vehicles or drive generators to generate electricity to supplement batteries [1]. The motor is one of the key components of the hybrid power system. Hybrid electric motor technology is related to the operational performance and efficiency of hybrid power systems. At present, the key technologies of hybrid electric motors mainly include high-speed motor technology, sensorless motor control technology, and motor vibration reduction control technology. The electromechanical coupling device is a component that couples mechanical drive, electric drive, variable speed regulation, and redistributes the total power after coupling. It is

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divided into three categories: torque coupling, speed coupling, and power coupling. Parallel connection adopts clutch + gearbox, and power splitting uses planetary gear; series-parallel DHT integrates multiple gears, clutch, and dual motors, achieving pure electric, parallel, and extended range mode switching [1]. For hybrid power systems with dual motor configurations, the electronic control management system communicates with EMS, MCU1, MCU2, BMS, and TCU through the CAN network. HCU receives the working status of each assembly in the power system and determines the power and torque output of the power system through controlling algorithm strategies based on the driver's accelerator pedal, brake pedal, and shift lever status, achieving management and control of various operating modes [2]. The auxiliary system includes the following two modules: the hybrid thermal management system, which simultaneously covers three sets of cooling circuits for the engine, motor, and battery; and the braking system, which integrates two mechanisms: hydraulic-mechanical braking and motor energy recovery braking. During sliding and deceleration, the motor reverses to generate electricity and store energy.

3.2. The structural composition of hydrogen fuel cell vehicles

The fuel cell vehicle system is divided into five core units: fuel cell engine system, onboard hydrogen storage system, electric drive system, auxiliary power system, and vehicle control system [3].

The fuel cell engine is the core of hydrogen fuel cell vehicles, which includes a fuel cell stack, an air supply module, a hydrogen supply module, a heat dissipation module, and an intelligent monitoring module. The fuel cell stack directly outputs direct current through the hydrogen-oxygen electrochemical reaction, without a combustion process, and the products only contain water and heat [3].

The mainstream of Chinese passenger cars is 70MPa carbon fiber composite high-pressure hydrogen storage bottles, which are equipped with hydrogen refueling ports, hydrogen pipelines, hydrogen safety valves, and leakage sensors. These bottles are responsible for storing high-pressure hydrogen gas and continuously supplying fuel to fuel cells [4].

The auxiliary power source is a high-voltage power battery. The electric drive includes a DC/DC boost converter, DC/AC inverter, drive motor, and reducer. The low-voltage DC power of the fuel cell is boosted to drive the motor, and during braking, the motor generates electricity in reverse and stores it in the power battery.

The vehicle controller VCU is the top-level control unit, which is connected to FC-ECU, BMS battery management, and MCU motor controller through the CAN bus to real-time control hydrogen flow rate, air intake volume, stack temperature, and power output distribution.

3.3. Quantitative performance comparison

The performance metrics of traditional hybrids and hydrogen fuel cells are compared in Table 1

Table 1. Comparison of performance metrics between traditional hybrid and hydrogen fuel cell

Performance Metrics	HEV/PHEV	FCEV
Maximum Conversion Efficiency of Power Source	Peak thermal efficiency of hybrid-specific engines: 41% -49% [4, 5]. Hybrid DHT transmission maximum efficiency: 97.6% [1]	Peak efficiency of fuel cell system: 63.7% [6]. Average comprehensive efficiency of FCEV vehicle: 62% [6]

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Table 1. (continued)

Energy Replenishment Duration	Fuel filling: 5-10 minutes [5]. PHEV slow charging: 4-8 hours, fast charging: 0.5-1 hour [5, 7]	High pressure hydrogenation: 3-5 minutes [8, 9]
Standard Comprehensive Endurance Mileage	Non plug-in HEV: 1100-1300 km [5]. PHEV with full fuel and full charge: 1500-2100 km [5]	70MPa hydrogen storage standard range: 600- 800 km [8]
WLTC Cycle Energy Consumption per 100 km	Non-plug-in HEV fuel consumption: 5.88-6.36 L [5]. PHEV fuel consumption: 2.9-8.4 L [5, 7]	0.81-1.67 kg hydrogen [6, 8]
0-100km/h Acceleration Performance Reference	5.2s (2370kg sample vehicle) [7]	5.4-7.0s (mainstream passenger cars) [6]
Power Attenuation under Low Temperature	Capacity of the battery decreases by 20% -30% [7]	No battery power attenuation, only hydrogen consumption increases [3, 6]
Exhaust Emissions	Contains CO_2 and a small amount of NOx	Zero exhaust, only water vapor
Full Lifecycle Carbon Emissions	PHEV：163 g/km [4]	Green hydrogen route 50 g/km; Grey hydrogen route 175 g/km [4]
Designed Service Life of Core Components	HEV power battery for 10 years or more [1]. Hybrid-specific engine: million-kilometer durability [1]	Passenger car fuel cell stack (2030 target): 8000 hours [6]. Commercial vehicle fuel cell stack (2030 target): 30000 hours [8]. Buffer power battery for 10 years or more [3]
Loss of The Entire Vehicle Transmission System	Existing mechanical losses in the clutch and gearbox, the transmission efficiency under high-speed direct drive conditions over 96%	No mechanical transmission mechanism, only electrically driven, with lower losses [3]

3.4. Qualitative advantage

3.4.1. Traditional hybrid vehicles (HEV/PHEV)

The core advantages of traditional hybrid technology are mainly reflected in three aspects: high infrastructure compatibility, thorough localization of the industrial chain, and significant energy-saving effects under multiple operating conditions. Hybrid electric vehicles can rely on existing fuel infrastructure to complete energy supply, without the need for new technical supporting facilities such as charging piles and hydrogen refueling stations, and have promotion advantages [1]. For China, P2.5, Single speed hybrid, planetary split hybrid DHT, and hybrid specific engines all have mature industrial chains and can achieve independent matching, with a high degree of localization; compared to the high manufacturing cost of hydrogen fuel cells, the purchase cost of hybrid vehicles in the same class is significantly reduced, and maintenance also relies on the existing fuel vehicle after-sales system, resulting in lower maintenance costs [5]. The hybrid system uses a dual energy supply form of fuel and electricity, which can compensate for the shortcomings caused by the

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constraints of existing battery energy density, fast charging, long-distance driving, and cold environments; The hybrid system can achieve multi-mode switching between pure electric, combined drive, and driving power generation through HCU control. In urban areas, low-speed electric motor drive is used to reduce fuel consumption, while high-speed engine direct drive ensures power. Energy allocation optimization can be achieved in multiple scenarios [1, 7]. The WLTC fuel consumption of traditional DCT fuel vehicles is 7.12L/100km, while that of single-speed hybrid vehicles is 5.88L/100km. The fuel saving rate of the same model exceeds 17%, and the effect is significant. The thermal efficiency of hybrid-specific engines can reach up to 48%, significantly reducing exhaust CO_2 and pollutant emissions compared to ordinary gasoline engines, meeting the dual carbon regulations [5].

3.4.2. Hydrogen fuel cell vehicles (FCEV)

The advantages of hydrogen fuel cells are reflected in the following aspects: hydrogen fuel cells rely on the electrochemical reaction of hydrogen and oxygen to work, with the only by-products being water and heat, and do not produce exhaust pollutants such as CO_2, nitrogen oxides, and particulate matter during vehicle operation; Proton exchange membrane fuel cells do not undergo combustion in electrochemical reactions and have completely zero emissions during the driving phase [3, 9]. Lithium batteries experience significant capacity degradation in low-temperature environments, while fuel cells do not rely on energy storage battery capacity for power output, resulting in stable power in harsh cold and high-altitude conditions. Also, the energy density of hydrogen is much higher than that of lithium batteries [3]. Fuel cell vehicles are more suitable for heavy-duty and long-distance transportation scenarios, and have stronger environmental adaptability [6]. The refueling process of 70MPa high-pressure hydrogen storage passenger vehicles takes only 3-5 minutes, eliminating the problems of fast charging heating and slow charging waiting for several hours, completely avoiding the problem of long-term charging of pure electric vehicles, and greatly improving the efficiency of fleet operation and long-distance travel [8, 9]. The energy sources of hydrogen fuel cells are diversified. Hydrogen can be produced by electrolyzing water through wind power and photovoltaics to produce green hydrogen, achieving renewable energy storage and breaking away from the single dependence on fossil fuels such as oil and natural gas, in order to assist the low-carbon transformation of the national energy structure and serve the long-term carbon neutrality strategy [6, 8]. Hydrogen fuel cell vehicles rely solely on the driving motor to output power, without internal combustion engine idle shaking or the mechanical shifting structure of the gearbox. The power output is linear and stable, with lower driving noise and a better driving experience [3]. The energy density of hydrogen gas is much higher than that of lithium-ion batteries. Under the same 600km range standard, the weight of the 70MPa hydrogen storage system is much lower than that of high-capacity power batteries. The advantage of vehicle lightweighting is obvious, reducing rolling resistance and energy consumption loss [8].

4. Existing problems and future development trends of two types of technologies

4.1. The current bottleneck and improvement measures of hybrid technology

4.1.1. Energy dependence issue

At present, hybrid vehicles are still powered by internal combustion engines and rely on fossil fuels. They continuously generate CO_2 and nitrogen oxides during operation, which can only reduce

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emissions but cannot achieve zero emissions during operation. PHEV carbon emissions have returned to the traditional fuel vehicle range, making it difficult to match the ultimate goal of medium - and long-term carbon neutrality [1, 4]. The hybrid dedicated engine is equipped with Miller cycle, low-pressure EGR, and high compression ratio technology, with a thermal efficiency of 41%-43% by 2025 and expected to increase to 46%-50% by 2030, reducing carbon emissions per unit mileage from the source; Popularize pure electric PHEV models with a range of over 150km, relying entirely on electricity for daily commuting and only using fuel for long-distance scenarios [1, 5].

4.1.2. Lower economic efficiency

Hybrid models are equipped with additional motors, high-voltage batteries, and DHT coupling transmission components, resulting in a premium of 20000 to 40000 yuan compared to gasoline vehicles of the same level. For users with lower annual driving mileage, fuel-saving benefits cannot cover the price difference of car purchase, and the economic payback time is long [5]. The engine, motor, and electronic control system can be highly integrated and designed to reduce the number of components and lower assembly and component costs; It also implements the policy of equal rights for oil and electricity, allowing hybrid vehicles to enjoy purchase tax reductions, urban road rights, and parking discounts simultaneously, reducing user usage costs [1].

4.1.3. Weak collaborative control of multiple systems and modules

Hybrid vehicles are equipped with engines, dual motors, multiple clutches, high-voltage batteries, and multiple power sources. The HCU vehicle controller has a high computational load, and mode switching in complex urban and mountain road conditions is prone to power lag and gear shifting jerks. In addition, series hybrid vehicles have high energy loss at high speeds, and complex power system control can easily cause driving jerks [2, 4]. Introducing model predictive control and reinforcement learning intelligent energy management algorithms to optimize the switching logic of vehicles can predict road conditions in advance and dynamically allocate engine and motor torque; And simplify the clutch shifting logic, reduce the frequency of power switching, and weaken the feeling of driving jolts [6, 9].

4.1.4. Decreases in battery performance at low temperatures

Under low temperature conditions, the capacity of HEV nickel-hydrogen and PHE lithium batteries decreases by 20%-30%, resulting in a significant reduction in pure electric range in winter and a decrease in economic efficiency under low temperature conditions. By equipping a battery liquid cooling preheating system, the battery cells are actively heated before starting the vehicle under low temperature conditions, increasing the available capacity under low temperature conditions compared to when not equipped; Optimize the SOC control window for battery charging and discharging to avoid accelerated aging of battery cells caused by deep charging and discharging, and to prevent a decrease in their ability to resist low temperature conditions [7].

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4.2. The current bottleneck and improvement measures of hydrogen fuel cell technology

4.2.1. High overall cost

The ability of China to produce components such as 70MPa carbon fiber hydrogen storage bottles and hydrogen circulation pump cores is insufficient, and the purchase price of FCEVs in the same class is about twice that of hybrid models. In China, the unit price of terminal hydrogenation is 60-70 yuan/kg, and the daily operating costs are relatively high [8]. To achieve large-scale production of carbon fiber hydrogen storage bottles, the manufacturing cost of containers should be reduced by more than 20% [8]. Also, concentrating on bulk procurement of vehicle equipment can dilute research and development and component manufacturing costs through bulk orders. As of 2022, China has only built 270 hydrogen refueling stations, and the coverage of urban and rural areas as well as high-speed road networks is limited; The high-pressure long pipe trailer can transport only 300kg of hydrogen per vehicle, resulting in high long-distance transportation costs. The initial infrastructure investment for large-scale industrial hydrogen pipelines is enormous [8]. Popularizing liquid hydrogen tank trucks to achieve large-scale and long-distance hydrogen storage and transportation can reduce unit hydrogen transportation costs; Developing a distributed electrolytic hydrogen production model within the station can also reduce the cost of long-distance hydrogen transportation [8].

4.2.2. Low domestication level and short lifespan of core materials

High-end products such as proton exchange membranes, carbon paper, and high-end platinum-based catalysts are basically monopolized by overseas markets for China [3, 8]. Moreover, the durability of proton exchange membranes limits the overall service life of the fuel cell stack [9]. Invest in the research and development of low-platinum, platinum-free iron-nitrogen-carbon new catalysts, reducing platinum loading to below 0.05g/kW and decreasing dependence on precious metals [3, 6]. And establish a recycling system for waste platinum metal to reduce the full-cycle cost of material use [9]. In addition, the development of domestically produced high-durability composite proton exchange membranes improves the stability of wet-dry cycle conditions and extends the overall life of the fuel cell stack [3].

4.2.3. Security risks due to lack of unified standards

The lack of unified industry standards for hydrogen storage, transportation, and refueling hinders the large-scale market promotion of fuel cells [9]. Firstly, unify 70MPa hydrogen storage tanks, hydrogenation facilities, etc., and then develop a complete set of relevant national standards to standardize the process of industry testing and safety supervision. Especially for on-board hydrogen storage: the explosion limit range of hydrogen is 4%-74.2%, and high-pressure conditions are prone to safety hazards such as hydrogen embrittlement and hydrogen leakage in pipelines [8]. So, to solve the problem of hydrogen storage safety, upgrading hydrogen storage bottles is a necessary approach, such as equipping leak sensors and automatic pressure relief safety control systems to reduce the risk of high-pressure leaks and explosions.

4.3. Future development trends

There are four major trends in the development of fuel cell technology. Firstly, modularization and serialization of fuel cells to adapt to the power requirements of different vehicle models, improve

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reliability, and reduce costs. Secondly, Electrification of the power system, shifting from fuel cells to "fuel cell + battery", improving battery life and reducing overall vehicle costs. Thirdly, 70Mpa high-pressure hydrogen storage has become mainstream, and hydrogen sources are localized and diversified. Fourthly, the technology of hydrogen fuel cell vehicles has shifted from individual research and development by car companies to deep integration between fuel cell companies and car companies, forming a win-win model [6, 10]. Many countries have incorporated hydrogen energy development into their national strategies and introduced supportive policies. The Chinese government strongly supports the hydrogen energy industry from both financial and policy perspectives, and promotes the construction of hydrogen refueling facilities. Currently, there are over 4500 FCVs and over 20 hydrogen refueling stations. It is planned to have 1 million FCVs and 1000 hydrogen refueling stations by 2030. In terms of hydrogen production, photocatalytic water splitting is also a promising renewable hydrogen production method. Currently, due to insufficient utilization of light and low hydrogen production efficiency, it is still in the laboratory research and development stage. The current research focus is on developing efficient, stable, and low-cost catalysts to improve the efficiency of photocatalytic water splitting hydrogen production and achieve industrial large-scale hydrogen production as soon as possible [11].

5. Conclusion

In summary, this article draws some conclusions through the analysis of traditional hybrid technology and hydrogen fuel cell engine technology. Hybrid power is currently the most cost-effective path to achieving energy-saving and emissions-reduction goals for automobiles. Compared with the same non-hybrid model, the strong hybrid power can reduce the average CO_2 emissions by about 30%, and the 10-year average fuel cost savings are much higher than the price premium. Hybrid technology is a long-term technological route that combines the advantages of traditional fuel vehicles and pure electric vehicles, with strong power, excellent fuel economy, and long driving range, and is not a temporary transitional solution. The market share of HEVs in the United States has increased from less than 3% in 2020 to about 10% in 2024, especially in California, which also confirms this trend.

Traditional hybrid technology is a relatively new technology that has made progress in environmental impact and energy utilization, and has profoundly changed the automotive industry. However, there are still issues of dependence on fossil fuels and battery life degradation, which affect its economy. Hydrogen fuel cell technology, as a new technology, demonstrates its enormous environmental benefits and sustainable development through its zero carbon emissions and more efficient energy conversion.

Hydrogen fuel cells are truly zero-emission technologies. Fuel cells convert hydrogen and oxygen into electrical energy through electrochemical reactions, with the only byproducts being water and heat, and do not produce any harmful emissions. Compared with other batteries, proton exchange membrane fuel cells (PEMFCs) have higher efficiency, environmental friendliness, and renewability. At the same time, their working principle is relatively simple, so they have broader application prospects compared to other batteries. Moreover, hydrogen fuel cells have significant advantages such as high efficiency and low noise. However, hydrogen fuel cells still face issues such as high cost, low durability, safe hydrogen storage, and limited infrastructure.

National policies, future research, and investment will focus on the issues and improvements of hydrogen fuel cells mentioned above, which is the key to the popularization of hydrogen fuel cell vehicles. At the same time, further strengthening public publicity and education, improving public awareness and acceptance of hydrogen fuel cell vehicles, can better promote hydrogen fuel cell

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vehicles. Hydrogen fuel cell vehicles are an important choice for sustainable development in the future. With the continuous iteration of technology and relevant policy support, hydrogen fuel cell vehicles will occupy a higher position in the global automotive market as environmental protection is gradually emphasized. They will make significant contributions to the sustainable development of the energy and automotive industries.

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