Development Status and Outlook of Hydrogen Internal Combustion Engine

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Hydrogen energy is one of the best energy carriers for achieving carbon peak and carbon neutrality, with the characteristics of high energy and no pollution. The hydrogen internal combustion engine is one of the important forms of hydrogen energy utilization, with the significant advantages of high efficiency, high reliability, low cost and low emissions. In this paper, the characteristics of hydrogen internal combustion engines and hydrogen fuel cells were compared, and the industrialization prospects of hydrogen energy utilization in the future were analyzed. Focusing on the hydrogen internal combustion engine technology system, a comprehensive analysis was conducted on the technical issues and technical progress in hydrogen storage, combustion, NO_x emissions, etc. of hydrogen internal combustion engines.

Keywords: Hydrogen internal combustion engine; Hydrogen storage; Combustion characteristics; Emission

Introduction

The current social energy system is dominated by disposable energy such as oil and natural gas. With the increase in energy demand, environmental pollution and greenhouse effect problems are becoming increasingly prominent. To achieve sustainable development, countries around the world are vigorously developing green energy such as solar energy, wind energy, and hydrogen energy. China has also put forward the strategic goals of reaching carbon peak by 2030 and carbon neutrality by 2060. Due to their inherent randomness and volatility, most renewable energy sources will produce serious losses of light energy, wind energy, etc. As a chemical energy storage energy source, hydrogen can effectively recover waste energy. Its high energy density (140 MJ/kg, 4.5 times that of coal, 3 times that of oil) and clean and pollution-free characteristics are regarded as the future energy technology direction [1, 2]. The use of hydrogen energy can reduce local pollution, lower global carbon dioxide emissions, and resolve the constraints of non-renewable energy such as oil and natural gas on human development.

The Structure, Material and Working Principle of Hydrogen Internal Combustion Engine

Hydrogen internal combustion engine, also known as hydrogen fuel engine, is an internal combustion engine using hydrogen as fuel. It basically follows the standard

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working principle of internal combustion engines, including four-stroke and two-stroke engines. This article focuses on four-stroke hydrogen internal combustion engines because they are more common in practical applications.

Hydrogen Internal Combustion Engine Structure

The structure of the hydrogen internal combustion engine is mainly composed of hydrogen supply system, combustion chamber, hydrogen and air mixing system, and cooling system. The hydrogen supply system includes hydrogen storage tank, hydrogen pipeline and injection system. Hydrogen is usually stored at high pressure and introduced into the engine through an appropriate injection system. The combustion chamber design needs to adapt to the characteristics of hydrogen, and usually requires higher ignition capacity and suitable combustion chamber shape to ensure sufficient combustion efficiency. The hydrogen and air mixing system is used to adjust and optimize the mixing ratio of hydrogen and air in the combustion chamber to achieve the best combustion efficiency and power output. The cooling system of internal combustion engines needs to adapt to higher operating temperatures, especially due to the heat generated by hydrogen [3].

Materials for Hydrogen Internal Combustion Engines

The materials used in the hydrogen internal combustion engine mainly include burner materials, valve and piston materials, and sealing materials. Burner materials require high temperature resistance and corrosion resistance. Common choices include special alloys or ceramic materials. Valve and piston materials also need to choose materials that can withstand high temperature and high pressure to ensure the long-term reliability and performance of the internal combustion engine. Due to the small molecular size of hydrogen, special sealing materials are needed to prevent hydrogen leakage.

Working Cycle of Hydrogen Internal Combustion Engine

The working cycle of the hydrogen internal combustion engine is divided into intake, compression, ignition, work and exhaust. The intake is to mix hydrogen and air into the combustion chamber. The compressed gas is compressed by the piston to increase its temperature and pressure. The ignition system ignites the mixture and causes combustion. The work process is that the energy of the gas drives the piston to move and generate power. The exhaust gas after combustion in the exhaust process is discharged through the exhaust valve [4].

Characteristics of Hydrogen Internal Combustion Engines

There are many ways to use hydrogen energy, among which hydrogen fuel cells and hydrogen internal combustion engines are the most concerned. Hydrogen fuel cells convert the chemical energy in hydrogen fuel directly into electrical energy through electrochemical reactions. They have high energy utilization, stable operating conditions and zero emissions, and were once considered the most effective way to utilize hydrogen energy. However, the high purity of hydrogen (99.99%), the dependence on the rare metal platinum, and the imperfect industrial system have led to the high price of hydrogen fuel cells. In the foreseeable period of time, it will be difficult for hydrogen fuel cells to meet the needs of the whole society through large-scale and industrialized production. On the contrary, although the hydrogen internal combustion engine is insufficient in terms of energy utilization and emissions, it is not much different from the traditional internal combustion engine in terms of structure, and the production of hydrogen internal combustion engine can rely on the existing industrial system to carry out mass production at low cost. On the whole, in terms of hydrogen energy utilization, hydrogen internal combustion is more promising for large-scale production and use in the automobile industry.

Hydrogen internal combustion engines have many advantages over hydrogen fuel cells. Most of the parts are the same as gasoline/diesel engines, and the material cost is about CNY 13,000. The existing production line can be used to save costs. The engine has high durability, about 300,000 km. It has low requirements for hydrogen purity and does not rely on rare metals. Overall, the biggest advantages of hydrogen-fueled engines lie in cost and industrialization prospects.

Development Status of Hydrogen Internal Combustion Engines

Up to now, hydrogen internal combustion engines have a history of development for several decades. As early as 2000, Ford officially began research on hydrogen internal combustion engines. Subsequently, foreign automobile companies such as BMW, Mazda and other automobile companies, and domestic companies such as Changan Automobile have all invested in the research and development of hydrogen internal combustion engines.

The development of hydrogen internal combustion engines has not been smooth sailing. During the in-depth research process, problems such as engine backfire, hydrogen embrittlement, and emissions have emerged one after another. BMW and other automobile companies have given up on exploring hydrogen internal combustion engines for cars due to reasons such as the inability to resolve the problem of on-board hydrogen storage, insufficient power caused by hydrogen injection in the airway, and imperfect hydrogen refueling stations. In the following years, the development of automotive hydrogen internal combustion engines stagnated. As time goes by, technology and materials continue to make breakthroughs, and problems such as storage, combustion, and emissions of on-board hydrogen have been effectively solved. Hydrogen internal combustion engines have regained attention in recent years. In 2019, SAIC Motor and Bosch Group respectively released 2.0-liter in-cylinder direct-injection turbocharged hydrogen internal combustion engines. Subsequently, in 2021, Toyota's hydrogen internal combustion engine vehicle Toyota-Corolla held a 24h rally at Fuji Circuit in Japan. In China, FAW, GAC, Great Wall and other automobile companies also launched different models of in-cylinder direct injection turbocharged hydrogen engine samples.

Overall, the research on hydrogen internal combustion engines can be divided into two phases: The first stage was from 2000 to 2007, the stage of gas-port hydrogen injection internal combustion engines developed by BMW. The second stage was from 2019 to the present, the stage of research and development of direct-injection hydrogen internal combustion engines represented by SAIC, Bosch and others.

Technical Problems and Development Status of Hydrogen Internal Combustion Engines

On-board Hydrogen Storage

The storage of hydrogen has always been a difficult problem in the research of hydrogen energy-related technologies. Hydrogen molecules are small in size and can easily penetrate into the interior of the storage tank material, hydrogenating the material and causing hydrogen embrittlement of the material. At the same time, the flammable and explosive nature of hydrogen restricts the application scenarios of hydrogen energy [5]. Especially in automotive engines, it is a huge challenge to store enough hydrogen fuel in a limited space to ensure mileage. At present, there are three main research directions of hydrogen storage methods: high-pressure gaseous hydrogen storage, low-temperature liquid hydrogen storage, and material-based hydrogen storage.

As early as the end of the nineteenth century, forged metal containers were used for hydrogen storage with a hydrogen storage pressure of 12 MPa. Because hydrogen molecules can easily penetrate into the cylinder to corrode the cylinder, resulting in hydrogen embrittlement. The cylinders are at risk of bursting under high pressure [6], and therefore are not used for on-board hydrogen storage. In 1963, Brunswick developed a high-pressure gas cylinder made of fully wound glass fiber composite material with a plastic liner. In 2001, Quantum successfully developed a high-pressure hydrogen storage cylinder with a carbon fiber fully wound structure with a polyethylene liner and a working pressure of 70 MPa.

In the automotive field, the most widely used hydrogen storage technology is high-pressure hydrogen storage cylinders. With the increasing demand for on-board hydrogen storage applications, light weight and high pressure are the final requirements for hydrogen storage cylinders. At present, high-pressure hydrogen storage containers have been developed from all-metal (type I bottles) to plastic liner fiber fully wound gas cylinders (type IV cylinders). The comparison of different types of high-pressure hydrogen storage cylinders is shown in Table 1.

Table 1. Comparison of different types of hydrogen storage bottles [5]

Type	Material quality	Working Pressure (MPa)	Cost	Vehicle available
Type I	Pure steel metal bottles	17.5~20	Low	No
Type II	Steel liner fiber winding bottle	26.5~30	Mid	No
Type III	Aluminum Liner filament winding bottle	30~70	High	Yes
Type IV	Plastic Liner filament winding bottle	>70	High	Yes

Type I hydrogen storage tank is not suitable for vehicle-mounted hydrogen storage because of its pure metal properties. Currently, Type III and Type IV are the mainstream composite hydrogen cylinders. It is mainly composed of inner liner and carbon fiber material. The fiber material is wound around the inner liner in a ring or spiral shape, which can effectively improve the structural strength of the inner liner. In the automotive field, Type IV hydrogen storage bottles have been successfully commercialized. However, China's research on high-pressure hydrogen storage started late. Limited by carbon fiber technology and filament winding technology, it is still committed to the development of Type III hydrogen storage bottles.

Deflagration, Pre-ignition and Tempering

The problems of hydrogen internal combustion engine are inseparable from its advantages. Firstly, the propagation speed of hydrogen combustion is extremely fast (about 9 times that of gasoline combustion), which will cause the combustion time to be too short and the combustion work time to be short. It cannot overcome the compression work and easily cause the engine to stall, that is, the deflagration problem. Secondly, because of the low ignition point of hydrogen, the overheating of the spark plug motor and the hot deposition in the internal combustion engine will lead to the natural occurrence of hydrogen and the problem of premature combustion. At the same time, due to the fast propagation speed of combustion, the intake valve has not yet closed at this time, and the flame will enter the intake pipe, causing backfire.

At present, enterprises are promoting direct injection technology, which injects hydrogen directly into the engine cylinder. This not only eliminates the problem of hydrogen occupying cylinder volume, but also greatly improves the power performance of hydrogen internal combustion engines. Compared with the intake port injection, the direct injection hydrogen internal combustion engine can inject hydrogen after the intake valve is closed to avoid the tempering problem caused by hydrogen backflow. The comparison of in-cylinder direct injection and inlet injection is shown in Table 2.

Table 2. Comparison of in-cylinder direct injection and inlet hydrogen injection [7]

Jetting method	Injection timing	Abnormal combustion	Mixture gas	Feature
Single poin injection of inlet	The initial stage of intake stroke	High risk tempering	Form uneven mixtu gas	Low sound power high combustion risk
Inlet multi-point injection	The end of the exhaust strol	Low risk backfir	Form a uniform mixture gas	Abnormal combustion risk
Direct injection	The initial stage of compression stroke	No tempering	Basically uniform	Low power

In a direct injection hydrogen internal combustion engine, uneven distribution of the mixer may cause premature ignition and detonation [8]. Verhelst *et al.* summarized the relationship between the knock intensity and the mass fraction of the unburned mixer. It can be concluded that the main methods of suppressing knock in hydrogen internal combustion engines are: optimizing the combustion chamber structure, optimizing the injection strategy, using EGR and water injection to reduce the temperature in the dry cylinder, and using the pressurization technology to improve the knock boundary [9].

Emission

In theory, hydrogen internal combustion engine has five emission products: H_2, HC, CO, CO_2 and NO_x. Among them, CO, CO_2 and HC are produced by oil combustion, and the emission concentration is small. As the main emission of hydrogen internal combustion engine, NOx is formed by the reaction of nitrogen and oxygen at high temperature of the cylinder, and the emission can reach 0.02 g/kW·h [10]. Therefore, controlling NO_x emissions is the key to controlling emissions from hydrogen internal combustion engines. At present, there are mainly the following means to reduce NO_x emissions.

Lean Burn and Injection Parameter Optimization

The NO_x emission of hydrogen internal combustion engine is closely related to the excess air coefficient λ. When λ reaches 2.5, it reaches the zero boundary point (as shown in Figure 1.

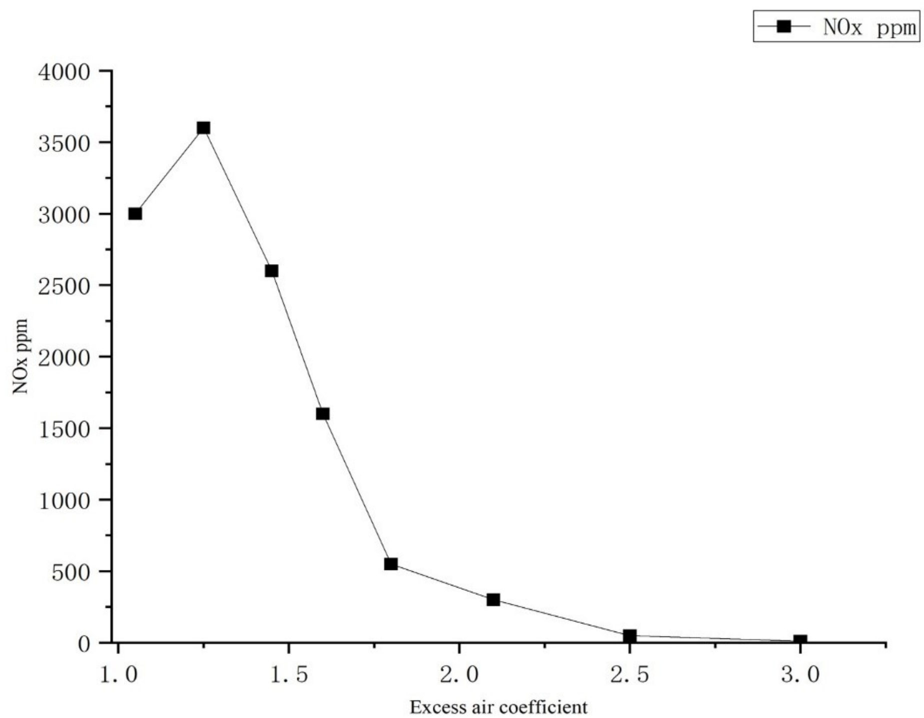

Fig. 1. Effect of excess air ratio on NO_x emissions

Therefore, controlling the excess air coefficient is the most effective way to reduce the emissions of hydrogen internal combustion engines. In order to ensure the combustion stability of the internal combustion engine, λ is generally less than 3.3. So, when λ is between 2.5 and 3.3, it can not only return the emission to zero, but also ensure the stability of hydrogen combustion. The intake pressure is increased by mechanical supercharging or turbocharging to ensure the power performance of the hydrogen internal combustion engine under lean combustion, so that the hydrogen internal combustion engine always works under the condition of λ > 2.5, and the emission is usually less than 0.1 g/kW·h.

Wanner *et al.* [11] studied the effect of injection phase on emissions, and concluded that the injection was advanced and the emission was reduced under partial load. Under heavy load conditions, delayed injection will lead to reduced emissions. This is because under some conditions, the overall combustion is thin, and early injection can extend the mixing time of the mixture to form a low concentration uniform mixture, reducing emissions. Under heavy load conditions, delayed injection can make the mixture in the cylinder stratified, avoiding the high emission stage to reduce emissions [12].

EGR Technology and Water Injection Technology

EGR (Exhaust Gas Recirculation) technology can significantly reduce the combustion temperature and combustion rate, thereby effectively reducing emissions [13].

The principle of the water injection technology is similar to that of EGR technology. But compared with the EGR technology, the water injection technology can more accurately control the combustion medium and combustion temperature without significantly affecting the power performance of the internal combustion engine. According to the injection method, the water injection technology can be divided into two forms: inlet water injection and direct injection in cylinder [14].

Post-Processing Techniques

In addition to the above-mentioned means of reducing in-cylinder emissions, further treatment of out-cylinder emissions is required to enable hydrogen internal combustion engines to meet increasingly stringent emission standards.

Tokyo City University in Japan has proposed a new exhaust emission after-treatment technology - a two-stage nitrogen oxide storage reduction system (NSR) and oxidation catalyst (DOC) combined system. The system works by utilizing incompletely burned hydrogen or injecting low-pressure hydrogen into the after-treatment system for reduction in the NSR, where the DOC system is responsible for the unreacted oxygen and ammonia produced during the oxidation-reduction process. According to the literature [15], the NO_x purification rate can reach 98%, while the hydrogen consumption only increases NO_x by 0.2~0.5 %. This set of post-treatment technology has a significant effect on vehicle operation, reducing cycle emissions from 1.07 g/kW·h to 0.08 g/kW·h. LNT (lean trap) and SCR (selective catalytic reduction) post-treatment technologies were studied [16]. By utilizing the concentration changes in the engine mixer, periodic adsorption-catalytic reduction and chemical reactions are carried out to completely remove a small amount of NOx emissions and achieve double zero emissions.

CONCLUSIONS

In recent years, great progress has been made in the practical application of hydrogen internal combustion engines. The industrialization prospect of hydrogen internal combustion engines is relatively bright. In the short term, hydrogen internal combustion engines are more suitable than hydrogen fuel cells for achieving carbon neutrality and carbon peak goals.

The hydrogen internal combustion engine has effectively solved the problems of hydrogen storage, combustion and emission, providing strong support for the future industrialization of hydrogen internal combustion engines. However, at the same time, under the current technical form, hydrogen storage technology and hydrogen injection technology need to be further improved. And because hydrogen fuel is different from diesel and gasoline fuel, we should get rid of the original internal combustion engine framework and establish a new hydrogen internal combustion system as soon as possible based on the characteristics of hydrogen fuel.

CONFLICTS OF INTEREST

The author declares that there is no conflict of interests regarding the publication of this paper.

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