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Development Status and Outlook of Hydrogen Internal Combustion Engine

Mengfei Liu [a*]

[a] China University of Water Resources and Electric Power, Zhengzhou City, No. 36, Beihuan Road, Henan, China.

Author's contribution

The sole author designed, analyzed, interpreted and prepared the manuscript.

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ABSTRACT

Hydrogen energy is the best energy carrier to achieve carbon peak and carbon neutrality, with high energy and pollution-free characteristics. Hydrogen internal combustion engine is one of the important forms of hydrogen energy utilization, which has 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 are compared, and the industrialization prospects of hydrogen energy utilization in the future are analyzed. Focusing on the technical system of hydrogen internal combustion engine, the technical problems and technical progress of hydrogen storage, combustion and NOx emission of hydrogen internal combustion engine are comprehensively analyzed.

Keywords: Hydrogen internal combustion engine; hydrogen storage; combustion characteristics; emission.

**Corresponding author: E-mail: 2593567927@qq.com;*

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1. INTRODUCTION

At present, the social energy system is based on one-time energy sources such as oil and natural gas, and with the increase in energy demand, the problems of environmental pollution and greenhouse effect are becoming increasingly prominent. In order to achieve sustainable development, countries around the world vigorously develop green energy such as solar energy, wind energy, and hydrogen energy, and China has also put forward the strategic goal of carbon peak in 2030 and carbon neutrality in 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, and its high energy density (140MJ/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]. Hydrogen is considered one of the most important fuels of the future. Its use will make it possible to meet increasingly stringent emissions standards. Currently, the hydrogen-powered internal combustion engine is the only known internal combustion engine that meets these strict EU regulations. A hydrogen-powered engine also emits significantly lower levels of other pollutant species compared to a diesel-powered engine [3].

2. 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 directly convert the chemical energy in hydrogen fuel into electrical energy through electrochemical reactions, with high energy utilization, stable working conditions, and zero emissions, which was once considered to be the most effective way to use 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 [4].

2.1 Advantages of Using Hydrogen Energy

(1) Reduce local pollution.
(2) Reduce global carbon dioxide emissions.
(3) Solve the problem of constraints on human development caused by non-renewable energy sources such as oil and natural gas.

2.2 Advantages of Hydrogen Internal combustion Engines Over Hydrogen Fuel Cells

(1) Most of the parts are the same as those of gasoline/diesel engines, and the material cost is about 13,000 yuan.
(2) The existing production line can be used to save costs.
(3) High durability, about 300,000 kilometers.
(4) Low requirements for hydrogen purity and no dependence on rare metals.

Overall, the biggest advantage of hydrogen-fueled engines is the cost and industrialization prospects.

3. DEVELOPMENT STATUS OF HYDROGEN INTERNAL COMBUSTION ENGINES

Up to now, the hydrogen internal combustion engine has a history of several decades of development, as early as 2000, Ford officially began the research of hydrogen internal combustion engine, followed by foreign automobile companies such as Baoma, Mazda and other automobile companies, domestic companies such as Changan Automobile and other companies have invested in the research and development of hydrogen internal combustion engine.

The development of hydrogen internal combustion engines has not been smooth sailing, and in the process of in-depth research, problems such as engine tempering, hydrogen embrittlement, and emissions have emerged one after another. Because the problem of on-board hydrogen storage cannot be solved, the lack of power caused by airway hydrogen injection, and the imperfection of hydrogen refueling stations, BMW and other automobile companies have given up the exploration of hydrogen internal combustion engines in automobiles. In the years that followed, the development of hydrogen internal combustion engines in automobiles came to a standstill. With the passage of time, there have been breakthroughs in technology and materials, and the problems of on-board hydrogen storage, combustion, and emissions have been effectively solved, and hydrogen internal combustion engines have been re-emphasized in recent years. In 2019, SAIC Motor and Bosch Group respectively released a 2.0-liter in-cylinder direct-injection supercharged hydrogen internal combustion engine. Subsequently, in 2021, Toyota's hydrogen internal combustion engine vehicle Toyota-Corolla held a 24h rally at Fuji Circuit in Japan, and in China, FAW, GAC, Great Wall and other automobile companies also launched different models of in-cylinder direct injection supercharged 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, when the airway hydrogen injection internal combustion engine stage represented by BMW AG; The second stage is the in-cylinder direct injection hydrogen internal combustion engine stage led by SAIC Motor and Bosch from 2019 to the present.

4. TECHNICAL PROBLEMS AND DEVELOPMENT STATUS OF HYDROGEN INTERNAL COMBUSTION ENGINE

4.1 On-Board Hydrogen Storage

The problem of hydrogen storage has always been a difficult problem in the research of hydrogen energy-related technologies, and the small size of hydrogen molecules is easy to penetrate into the storage tank material to hydrogenize the material, resulting in hydrogen embrittlement. 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 range. At present, there are three main research directions of hydrogen storage methods: high-pressure gaseous hydrogen storage, low-temperature liquid hydrogen storage, and hydrogen storage material 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 12M.Because hydrogen molecules can easily penetrate into the cylinder to corrode the cylinder, resulting in hydrogen embrittlement, the cylinder has the risk of bursting under high pressure [6], so it is not used for on-board hydrogen storage. In 1963, Brunswick developed a plastic liner glass fiber fully wound composite high-pressure gas cylinder. 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 70MPa.

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]

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

Type I hydrogen storage tank is not suitable for vehicle-mounted hydrogen storage because of its pure metal properties. At present, type III and type IV are the mainstream of composite hydrogen production 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 abroad; 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.

4.2 Deflagration, Pre-Ignition and Tempering

The problems of hydrogen internal combustion engine are inseparable from its advantages. The propagation speed of hydrogen combustion is extremely fast (about 9 times as fast as that of gasoline combustion), which will lead to too short combustion time and short combustion work time, unable to overcome the compression work, and easily lead to engine flameout, that is, 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, because the combustion propagation speed is fast, the intake valve is not closed at this time, the flame will enter the intake pipe, and the tempering phenomenon will occur [7,8]

At present, companies promote direct injection technology to directly inject hydrogen into the engine cylinder, which not only eliminates the problem that hydrogen occupies the cylinder volume, but also greatly improves the power performance of the hydrogen internal combustion engine. 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 [7].

The use of in-cylinder direct injection hydrogen internal combustion engine will cause premature ignition and detonation due to the uneven distribution of the mixer [9]. S. Verhelst 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 [10].

4.3 Emission

In theory, hydrogen internal combustion engine has five emission products : H_2, HC, CO, CO_2 and NO. 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, it is formed by the reaction of nitrogen and oxygen at high temperature of the cylinder, and the emission can reach 0.02g/kW·h [11]. Therefore, the controlled emission is the key to control the emission of hydrogen internal combustion engine. At present, there are mainly the following means to reduce emissions.

(1) Lean burn and injection parameter optimization

The 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 Fig. 1).

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 $\lambda > 2.5$, and the emission is usually less than 0.1 g / kW · h.

T. Wanner et al. studied the effect of injection phase on emission, 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].

(2) EGR technology and water injection technology

EGR (Exhaust Gas Recirculation) technology, through EGR technology, can significantly reduce the combustion temperature and combustion rate, thereby effectively reducing emissions [10]. C. Bleechmore compared the effects of cold and hot EGR on the hydrogen internal combustion engine, and the emissions were reduced by 87 % and 93 %, respectively, at the chemical equivalent concentration. At the same time, the use of cold EGR will affect the combustion stability, and the average effective pressure cyclic variation coefficient increases from 1.7% to 2.6%.

The principle of water injection technology is similar to that of EGR technology, but compared with EGR technology, water injection technology can more accurately control the combustion medium and control the combustion temperature, and will not greatly affect the dynamic performance of 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.

(3) Post-processing techniques

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

A new type of exhaust emission aftertreatment technology, a two-stage nitrogen oxide storage and reduction system (NSR) and oxidation catalyst (DOC) combined system, was proposed at the City University of Tokyo, Japan. The working principle of the system is to use incompletely burned hydrogen or inject low-pressure hydrogen into the aftertreatment system

Table 2. Comparison of in-cylinder direct injection and inlet hydrogen injection characteristics

Type	Material quality	Working pressure	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	Aluminium Liner filament winding bottle	30~70	High	Yes
Type IV	Plastic Liner filament winding bottle	>70	High	Yes

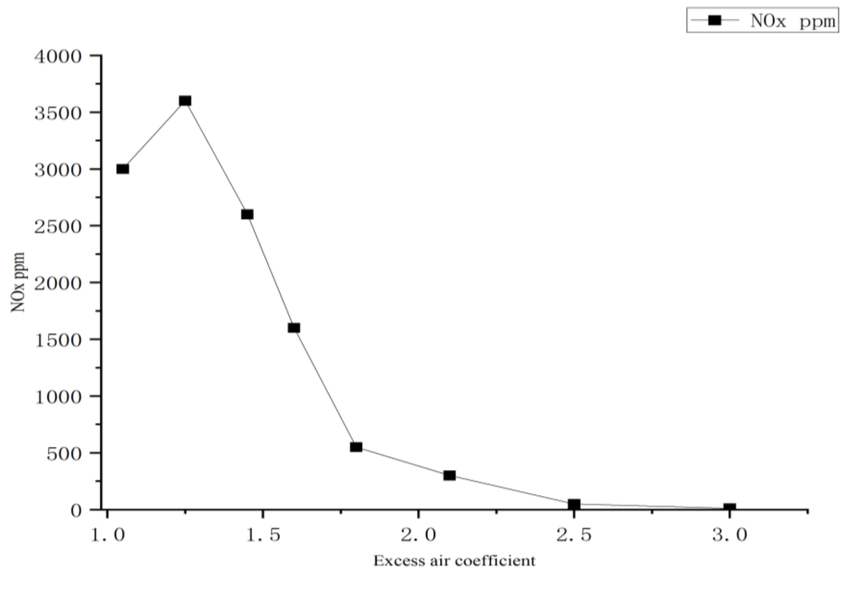

Fig. 1. Effect of air coefficient on emissions

to reduce in the NSR, where the DOC system is responsible for oxidizing unreacted oxygen and ammonia generated during the reduction process [13]. It can be seen from Reference that the purification rate of NOx can reach 98 %, while the consumption of hydrogen only increases by 0.2% ~ 0.5% NOX. This set of post-processing technology has a more obvious effect on the operation of the vehicle, which can reduce the cycle emission from 1.07g/ kW·h to 0.08g /kW·h. LNT (lean trap) and SCR [14]. (sele ctive catalytic reduction) post-processing technologies were studied. Periodic adsorption-catalytic-reduction and chemical reaction were carried out by using the concentration change of engine mixer to completely remove a small amount of NOx emission and achieve double zero emission.

5. 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 clear. In the short term, hydrogen internal combustion engines are more suitable than hydrogen fuel cells for achieving carbon neutralization and carbon peak goals.

Hydrogen internal combustion engine can solve the problems of hydrogen storage, combustion and emission, and it will be a powerful support for the development of HCI. But at the same time, in the present technology, the technology of hydrogen storage and hydrogen injection still needs to be improved. Since hydrogen is different from diesel and petrol, it is necessary to discard the old frame of the internal combustion engine and build a new type of hydrogen fuel as quickly as possible.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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