The Applications and Prospects of Hydrogen Internal Combustion Engine

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Abstract. Hydrogen internal combustion engines (HICs) are an emerging technology with significant potential for clean energy propulsion. However, they currently face several technical challenges, such as abnormal combustion phenomena, low energy density, and complexities in control under transient operating conditions. The primary technological focus areas include the integration of hydrogen combustion systems, ensuring safety, and enhancing reliability. HICs are vital for promoting environmental protection and sustainable development due to their potential for reducing greenhouse gas emissions. This paper provides an in-depth analysis of the current state of HIC technology, addressing key challenges and recent research efforts aimed at overcoming these issues. The discussion includes advancements in combustion technology, safety measures, and reliability improvements. With continued innovation, HICs are expected to become a viable alternative in various applications, supporting the global transition to cleaner energy solutions. This overview underscores the importance of further research and development to realize the full potential of hydrogen internal combustion engines.

Keywords: Hydrogen internal combustion engines, energy density, fuel, abnormal burning.

1. Introduction

The current approach of using fossil fuels as the main form of energy supply to meet the world's energy needs is becoming increasingly untenable. Fossil fuel reserves, which were once virtually unconsidered, have clearly been depleted [1]. Global warming and local pollution hot spots associated with fossil fuel use are further serious environmental and social problems. These issues also give a strong impetus to research, development and demonstration of alternative energy sources.

Hydrogen, on the other hand, has received a great deal of attention early on as an excellent clean energy source. HICs have also gradually gained much attention as a way of using hydrogen. A HIC, also known as a hydrogen fuel engine or HIICE is a power plant that uses hydrogen as fuel. Its basic principle is similar to that of a conventional internal combustion engine in that it burns fuel to generate thermal energy, which is then converted into mechanical energy to drive the machine. However, unlike traditional internal combustion engines that use fossil fuels such as petrol or diesel, the HIC uses hydrogen as its main fuel, which can effectively solve the energy crisis without generating a large amount of exhaust gas.

Of course, the hydrogen combustion engine has a number of limitations and shortcomings that prevent it from fully replacing the traditional combustion engine. Hydrogen is flammable and explosive, which puts higher requirements on safety management and requires special safety measures to ensure the safety of hydrogen during storage, transport and use, which also leads to relatively high costs of hydrogen, further increasing the cost of hydrogen combustion engines and their fuels, and restricting their market promotion. At the same time, hydrogen combustion engine technology has not yet reached a mature stage, and there are still a large number of technical challenges to be overcome, requiring further research development and improvement, which will also increase its cost. This paper describes the advantages and technical difficulties of HCIs, describes some of the core technologies of HCIs, and discusses the development prospects of HCIs.

2. Unique Merits of HIC

The most significant advantage of the HIC is its environmental friendliness. With the increasing depletion of global oil resources and fluctuating prices [2], the search for alternative energy sources has become an important task for governments and enterprises. Unlike traditional gasoline or diesel internal combustion engines, HICs generate mainly water vapor during the combustion process, producing few greenhouse gases and other harmful substances. This green emission characteristic makes HICs show great potential in combating global climate change and environmental protection while at the same time helping to reduce the dependence on petroleum resources and promote the diversification of the energy mix.

Hydrogen, as a high energy density fuel, contains much more energy per unit mass than petrol and diesel. As a result, HICs can provide strong power while ensuring a longer range (Fig. 1). This is particularly important for vehicles that have to travel long distances or work under high loads. In addition, the fast combustion speed and moderate temperature of hydrogen give hydrogen combustion engines the advantage of thermal energy conversion, which further improves the efficiency of energy utilization [2].

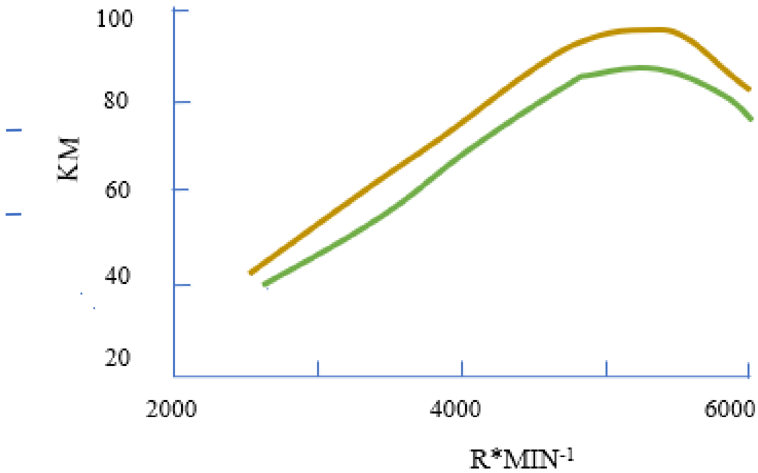

Figure 1. Comparison between the CNG engine and the base gasoline engine [3].

The fast combustion speed and moderate temperature of hydrogen give the HIC an advantage in thermal energy conversion. Compared to conventional internal combustion engines, HICs are able to convert the chemical energy of the fuel into mechanical energy more efficiently, thus improving the performance and efficiency of the engine. This efficient conversion of thermal energy results in excellent performance in terms of power output and fuel economy.

3. Main Technical Difficulties of Hydrogen-Fueled Internal Combustion Engines

3.1. Abnormal Burning

In internal combustion engines using hydrogen as a driving force, a number of atypical combustion challenges are encountered when hydrogen is injected directly through the intake system for combustion. Specifically, these challenges include, but are not limited to, the phenomenon of backfiring - where the flame propagates backward through the intake tract, potentially leading to erratic engine performance [4]; the problem of premature ignition, which refers to the premature start of the combustion process, potentially triggering knocking noises and damaging engine components; and the phenomenon of detonation, which is a violent, uncontrolled form of combustion that can seriously affect engine smoothness and durability.

3.2. Low Energy Density

The volumetric theoretical air-fuel ratio for hydrogen is only 2.38, a value that reveals a significant volumetric proportion of hydrogen in the mixture, which directly limits the engine charge factor, i.e., the amount of fresh air drawn into the cylinder per cycle, and thus the power output of the internal combustion engine. In addition, due to the presence of premature ignition, the mixture needs to be prepared more carefully to avoid over-concentration in order to prevent uncontrolled combustion processes, a limitation that further reduces the potential power output of the internal combustion engine, thus affecting the overall performance.

3.3. Pollution-Related Problems

A significant feature of hydrogen combustion is its high-temperature characteristics. Usually, the combustion temperature can be more than 2000 K. Under the conditions of high temperature and high mixture concentration, the generation of nitrogen oxides (NOx) increases significantly, especially in the rich combustion region where the equivalent combustion-to-air ratio is greater than 0.5, the emission of NOx rises sharply, which has become a non-negligible environmental pollution problem. This requires HICs to take effective measures, such as optimizing the combustion process and adopting after-treatment technologies, to reduce NOx emissions during design and operation [5].

3.4. Control Challenges Under Transient Conditions

The control strategy of a HIC is particularly complex due to the uniqueness of its fuel characteristics. Under different load conditions, the fuel injection volume and ignition timing must be precisely adjusted to achieve optimal combustion and power output. However, in forklift trucks and other equipment that frequently undergo variable operating conditions, especially when the load is suddenly increased at low speeds, it is technically difficult to ensure the rapidity and consistency of the transient response. This requires not only a high degree of flexibility and responsiveness of the control system but also an in-depth understanding of the dynamic characteristics of the hydrogen combustion engine and a precise control strategy.

4. Some Key Technologies in the Field of HICs

4.1. Hydrogen Combustion System Integration Technology

In view of hydrogen's fast combustion speed, flammability and explosiveness, and low density, its combustion system integration technology has become the core to ensure the efficient and stable operation of the engine. Among them, the high-pressure multi-point intake tract injection technology effectively improves the homogeneity of the mixture [6], reduces the tendency of detonation, and optimizes combustion efficiency by precisely controlling the time and amount of hydrogen gas injected into the intake tract. In addition, the high-pressure direct injection technology further refines the combustion process, enabling the hydrogen to ignite quickly closer to the spark plug or ignition source, improving the combustion rate and energy conversion efficiency [6]. High-pressure, low-inertia turbocharging technology reduces the turbine's moment of inertia to achieve a faster response speed, effectively matching the rapid characteristics of hydrogen combustion and enhancing the engine's low-speed torque and overall power performance. The combined application of these technologies not only improves the economy and power of the engine but also significantly enhances the reliability and durability of the system.

4.2. Security Technology

Modern HIC technology adopts a variety of innovative means to suppress the potential safety hazards of premature ignition, backfiring and knocking that may occur during hydrogen combustion. Premature ignition suppression technology effectively reduces the risk of premature ignition due to localized high temperatures by optimizing ignition timing, enhancing air movement in the cylinder and using high-temperature resistant materials. Flashback suppression technology prevents the unburned mixture from flowing back into the intake tract or hydrogen supply system by using a specially designed intake and exhaust system structure and pressure management strategy to ensure safe system operation. The knock suppression technology combines advanced knock detection sensors and intelligent control algorithms to monitor and adjust the ignition advance angle in real time to avoid the knock phenomenon caused by excessive combustion pressure, protecting the engine from damage. The combined use of these safety technologies provides a solid safety guarantee for the wide application of HICs.

4.3. Reliability Technology

In order to improve the reliability of HICs, transient responsive control technology and hydrogen supply system safety control technology have become key. By optimizing the engine control strategy, the transient responsive control technology achieves fast and accurate adjustment of engine speed, load and other parameters and improves the stability and response speed of the engine under transient working conditions. Meanwhile, the hydrogen supply system safety control technology covers various aspects such as hydrogen storage, delivery, distribution leakage detection, etc. By adopting high-strength hydrogen-resistant materials, designing a reliable sealing structure, and installing intelligent leakage detection devices, the safe and reliable operation of the hydrogen supply system is ensured. For example, the hydrogen fuel engine electronic control system is shown in Fig. 2. The continuous optimization of these reliability technologies not only extends the service life of the hydrogen combustion engine but also reduces its operation and maintenance costs, laying a solid foundation for the commercial application of hydrogen combustion engines.

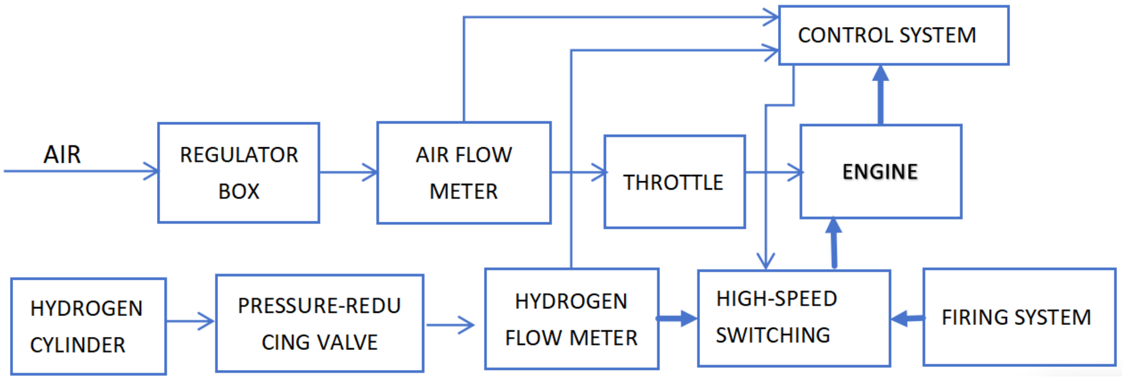

Figure 2. Hydrogen fuel engine electronic control system (Picture credit: Original)

5. The Perspectives on the Future of HIC

Currently, the hydrogen energy industry is in its early stage of development, and as an important part of the future energy system, it is receiving extensive attention and active layout from countries around the world. According to the authoritative forecast of the International Hydrogen Energy Council, by 2050, hydrogen energy will be responsible for 18% of the world's energy end-use demand, of which fuel cell vehicles will occupy a significant share of the global vehicle fleet and hydrogen combustion engine commercial vehicles are also expected to occupy a place in this market. The Hydrogen Energy Coalition optimistically estimates that by 2050, the demand for hydrogen energy in the transport sector will reach 24.58 million tons or nearly 20%.

Although hydrogen combustion engines show significant advantages in terms of environmental friendliness, high energy efficiency and fast replenishment, the road to their development is not a straight one. Storage and transport challenges, safety concerns, high costs, environmental friendliness of hydrogen sources, and lack of technological maturity are still bottlenecks that limit its widespread application. However, with the rapid advancement of technology and the acceleration of the global energy transition, these problems are gradually being solved. Technological innovations are continuously reducing production costs and improving the safety and efficiency of hydrogen utilization; at the same time, governments and enterprises have introduced policies and financial support, paving the way for the development of HICs [7,8].

6. Conclusion

The HIC, as a not-yet-mature field, faces a series of technical challenges and opportunities. Firstly, anomalous combustion and low energy density are urgent issues that directly affect engine performance and efficiency. Secondly, how to effectively control the operation of HICs under transient conditions is also the focus of technology development. To address these challenges, a number of key technologies have emerged. Among them, hydrogen combustion system integration technology helps optimize the combustion process and improve efficiency; safety technology ensures the safety of HICs in operation; and reliability technology guarantees their long-term stable operation. As an important direction of clean energy technology, the research and development of HIC is of great significance in promoting green transport and energy transformation. In the future, with the continuous progress of technology, HIC is expected to play a greater role in the field of environmental protection and energy. Looking ahead, HICs are expected to shine in the field of clean energy vehicles. With the gradual improvement of hydrogen refueling stations and other infrastructures and the increasing acceptance of consumers, HIC vehicles will gradually realize the leap from the special field to the mass market. In addition, the continuous upgrading and optimization of HIC technology will further enhance its performance, providing greener, more efficient and more convenient power support for future transportation. All in all, the development prospect of HIC is worth looking forward to, and it will become an important force to promote the global energy transition and sustainable development.

References

[1] Yi Qing, Wang Wei, Fei Youzhi, et al. Application and popularization of hydrogen internal combustion engine. Chinese Journal of Electrical Engineering, 2021, 1: 219 - 221.

[2] Yao Baofeng, Li Guoxiu. Comparison between nature gas and hydrogen for vehicle engine. Journal of Beijing Jiaotong University, 2005, 2: 99 - 103.

[3] Skea Jim, Diemen Renée van, Portugal-Pereira Joana, et al. Outlooks, explorations and normative scenarios: Approaches to global energy futures compared. Technological Forecasting and Social Change, 2021, 168: 120736.

[4] Kolosok Svitlana, Bilan Yuriy, Vasylieva Tetiana, et al. A scoping review of renewable energy, sustainability and the environment. Energies, 2021, 14 (15): 4490.

[5] Sun Hai. Hydrogen energy is arousing great attention all over the world. International Journal of Hydrogen Energy, 2020, 46 (3): 2845 - 2846.

[6] Dong Ningning, Yin Chenbo, Zhang Zili, et al. Research progress in hybrid power construction machinery and hydrogen engine, Journal of Mechanical & Electrical Engineering, 2011, 11: 1300 - 1305.

[7] Wang Lei, Experimental study of hydrogen and addition of hydrogen to natural gas on a spark ignition engine. Shanghai Jiao Tong University Shanghai, 2009.

[8] Ma Fanhua, Wang Yu. Study on the extension of lean operation limit through hydrogen enrichment in a natural gas spark-ignition engine. International Journal of Hydrogen Energy, 2008, 33: 1416 - 1424.