Hydrogen-Doped Combustion Engines: Present and Future

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Abstract. The development of clean energy is an important research direction in the face of global climate change and chemical fuel shortages. Hydrogen is receiving increasing attention as a clean energy source due to its properties of reducing carbon emissions and improving the performance of internal combustion engines. This paper provides an overview of the current state of research on hydrogen-doped internal combustion engines and analyzes the combustion characteristics of hydrogen, its impact on engine performance, and the technical challenges associated with carbon and nitrogen emissions. The study uses a literature review approach to summarize data on the hydrogen doping ratio on fuel efficiency and emissions. The results show that doping internal combustion engines with 5% to 30% hydrogen can increase engine efficiency by 25% while reducing harmful emissions such as CO and HC by 40% to 80%. However, NOx emissions NOx emissions increase with increasing hydrogen content. To avoid this, a mix of exhaust gas recirculation (EGR) and lean-burn technologies is essential. These technologies make hydrogen-doped internal combustion engine technology a great potential for heavy-duty vehicles.

Keywords: Hydrogen, Internal combustion engine, NOx emission.

1. Introduction

Today, global climate change and shortage of fossil fuels are the energy problems people are facing. Hydrogen is the answer to these problems. Hydrogen, as a clean and efficient fuel, has become the focus of research in the field of internal combustion engines because it produces almost no CO_2 during combustion and has a high combustion efficiency, which can effectively reduce greenhouse gas emissions and environmental pollution. By blending hydrogen with conventional fuels, hydrogen doping technology is expected to reduce pollutant emissions and improve engine performance without significantly altering the existing internal combustion engine architecture.

This paper will focus on the current research status of hydrogen blended internal combustion engines, systematically review the combustion characteristics of hydrogen and its effects on the performance of internal combustion engines, and thoroughly discuss the technical bottlenecks encountered in the current applications, such as the increase in NOx emissions and hydrogen storage problems [1]. This paper adopts a literature review to analyze the experimental data and modeling studies on different hydrogen blending ratios, combustion characteristics and engine performance. The review aims to provide a reference for the further optimization of hydrogen doping technology for internal combustion engines in the future, and to explore how to enhance the practical application potential of hydrogen energy through technological improvements.

2. Effects of hydrogen doping on engine performance

In recent years, the potential for energy saving and emission reduction demonstrated by hydrogen doping technology has received increasing attention from researchers. This paragraph highlights the effects of different blending ratios on the performance, combustion and emissions of internal combustion engines [2].

2.1. Effect of hydrogen blending ratio in different fuels on engine performance

When hydrogen is blended in a gasoline engine at a ratio of 5% to 20%, the total thermal efficiency of the engine rises by 10% to 15% year-on-year. When the hydrogen blending ratio reaches 30% or even higher, the thermal efficiency can be increased by 20% to 25%.

For fuels blended with natural gas and hydrogen, when the hydrogen blending ratio is 20% to 30%, it not only significantly improves the combustion stability of the engine and extends the lean burn limit, but also reduces greenhouse gas emissions. In addition, hydrogen has high diffusivity and high combustion speed, which effectively compensates for the slow combustion of natural gas, enabling the blended fuel to burn stably at higher altitudes where the air is thinner.

Blending with hydrogen is also possible in diesel engines. Experimental data show that diesel engines blended with 10-30% hydrogen have improved thermal efficiency by 5-15% under different load conditions. It was also found that engines running on dual-fuel hydrogen and diesel had lower carbon emissions without compromising power output.

2.2. Engine modifications and control systems

In order to adapt to the combustion characteristics of hydrogen, Direct Injection (DI) technology is adopted to achieve higher thermal efficiency at high pressure and to avoid pre-ignition and detonation. For example, at high loads, the thermal efficiency of a hydrogen engine with Direct Injection at 300 bar can be as high as 45%.

In addition, experiments have shown that combustion efficiency can be significantly improved and NOx emissions reduced by optimizing the control system to precisely control the timing of the hydrogen injection and the fuel mixing ratio. Combined with exhaust gas recirculation (EGR) technology and appropriate cooling measures, NOx emissions due to high combustion temperatures can be targeted.

3. Combustion

Hydrogen as an auxiliary fuel in an internal combustion engine has unique combustion characteristics, and these characteristics can affect engine performance and emissions at different blending ratios. The behavior of hydrogen combustion at different ratios is discussed in this paragraph.

3.1. Combustion characteristics of hydrogen

Hydrogen has a high combustion rate and a wide range of combustion limits, and is capable of co-firing with numerous mixtures in very thin air. Specifically, under stoichiometric conditions, the flame speed of hydrogen is 1.85 m/s, while gasoline is only 0.37-0.43 m/s, and the flame propagation rate of hydrogen is four times that of gasoline. In addition, hydrogen has a lower tendency to detonate, which is due to the high auto-ignition temperature of hydrogen, which reaches 858K [3].

3.2. Advantages of hydrogen doped combustion

Hydrogen's high diffusivity helps it form a more homogeneous fuel mixture, resulting in better mixing than conventional fuels. Hydrogen can be operated under lean combustion conditions, thereby reducing harmful emissions. Studies have shown that the calorific value of hydrogen combustion is 120 MJ/kg, nearly three times that of gasoline (gasoline is 44 MJ/kg), so combustion of hydrogen not only improves thermal efficiency but also reduces pollutant emissions [4].

3.3. Technical challenges of hydrogen doping combustion

When hydrogen is combusted under numerous mixture combustion conditions, high temperatures can be generated, which can lead to an increase in NOx. This is due to the high combustion rate and low ignition energy characteristics of hydrogen. In addition, the flame extinguishing distance of hydrogen is only 0.64mm, which is smaller compared to gasoline's 2.84mm, meaning that hydrogen flames are able to propagate to smaller gas seams, which can lead to knocking and backfires.

4. Emission

Hydrogen doping and combustion has been shown to reduce carbon emissions, but NOx generation is still a concern due to the properties of hydrogen itself, and this paragraph will analyze the emissions resulting from hydrogen combustion.

4.1. CO_2, CO and HC emissions

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4.2. Emissions of NOx and other pollutants

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Since hydrogen is carbon free, it virtually avoids carbon soot and particulate emissions and significantly reduces particulate matter (PM) emissions compared to conventional fuel engines.

5. Future directions for hydrogen-doped internal combustion engines

5.1. Technological improvements and application prospects

The goal of future development of hydrogen-doped internal combustion engines is to continue to improve efficiency and reduce emissions. Research has shown that the use of Direct Injection (DI) can significantly improve combustion efficiency at high pressures. For example, the thermal efficiency of a 300bar high pressure Direct Injection hydrogen doped engine can be as high as 45% under high load conditions. In addition, the continued development of lean-burn and EGR technologies can sustainably reduce NOx emissions, resulting in NOx reductions of 40% to 50% year-over-year.

5.2. Trends in Hybridization and Electrification

In the future, hydrogen-doped internal combustion engines and electrification technologies will be combined to form hydrogen-electric systems. Such a system will be able to utilize the advantages of hydrogen combustion at high loads and make up for the loss of power through the use of electric power at low loads, thus significantly improving overall energy efficiency. The system is particularly suitable for long-distance transportation and heavy-duty trucks, and can effectively reduce fuel consumption and carbon emissions [5].

5.3. Additional Point: Hydrogen Storage and Infrastructure Challenges

Hydrogen storage and transportation lags far behind conventional fuels such as gasoline. Unlike conventional fuels, hydrogen has a low density and needs to be compressed at high pressure (typically 700 bar) or cooled to low temperatures (about -253°C) for storage. Current storage methods, such as compressed gas cylinders and liquid hydrogen tanks, not only have safety concerns, but also add considerable cost to long-distance buses. In addition, the storage and distribution of high-pressure hydrogen requires a hydrogen distribution network formed by the construction of hydrogen refueling stations. But a lack of infrastructure in many remote areas limits the use of hydrogen combustion engines. Therefore, to overcome these challenges, more research should be done on hydrogen storage

materials in the future. In addition, the government should encourage the construction of hydrogen infrastructure and provide preferential policies [6].

6. Summary

Through the study of hydrogen doped internal combustion engines, this review summarizes the significant advantages of hydrogen as a clean fuel in reducing carbon-based emissions. Hydrogen is very pure and does not produce carbon-based pollutants such as CO_2, CO, particulate matter, etc. when burned, which makes it an ideal clean energy source. Research results have shown that hydrogen doping technology can reduce carbon emissions from internal combustion engines by more than 50 percent. However, the high temperatures resulting from hydrogen combustion can lead to an increase in NOx emissions, which is the biggest challenge facing hydrogen-doped internal combustion engines today. To address this issue, the use of both lean-burn and EGR technologies together has proven to be an effective means of controlling the problem, which can significantly reduce combustion temperatures and prevent NOx emissions by up to 40% to 50%, thus reducing the impact on the environment.

This study provides a solid foundation for the further development of hydrogen doping technology in internal combustion engines in the future, bridging the gap of hydrogen energy application in this field, which is especially suitable for long-distance transportation vehicles and other areas with high fuel consumption. In the future, optimizing the injection system and controlled combustion strategies for hydrogen should be the focus of future research to improve combustion efficiency and reduce harmful emissions. At the same time, the promotion and application of hydrogen-doped internal combustion engines can not be separated from the government's support and technological advances to accelerate the marketization of this technology in order to achieve the goal of “carbon neutrality” and “carbon peak”.

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