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A Brief Analysis of Hydrogen Engine Technology Development

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Abstract. With increasing global attention on environmental protection and sustainable development, hydrogen engines have garnered extensive research and interest as a promising clean energy power source. This paper reviews research progress on the combustion and emission characteristics of hydrogen engines. As well as, it details the combustion process of hydrogen engines, including flame propagation and combustion velocity, and thoroughly analyzes the various factors that influence combustion behavior. Simultaneously, it explores the emission characteristics of hydrogen engines, focusing on the formation mechanisms and control methods for primary pollutants such as nitrogen oxides (NOx). Through intensive research and development in hydrogen storage technology, it will be possible to achieve high storage density, low cost, and safe, efficient large-scale hydrogen storage, which is crucial for advancing China's hydrogen energy industry. Ultimately, it outlines future research directions and development trends for hydrogen engines, aiming to provide a reference for further advancements in hydrogen engine technology.

Keywords: Hydrogen engine, Combustion characteristics, Emission characteristics, Hydrogen storage, Research progress

1. Introduction

The accelerated pace of global industrialization has led to the extensive consumption of traditional fossil fuels, exacerbating issues of energy depletion and environmental pollution. Against this backdrop, the development and utilization of clean energy have become critical to addressing these challenges. Hydrogen, as a clean and efficient energy carrier, offers advantages such as pollution-free combustion products and high energy density, positioning it as a key direction for future energy development. Hydrogen engines, a primary method for utilizing hydrogen in the power sector, generate thermal energy through the combustion of hydrogen and convert it into mechanical energy, providing power for vehicles, power generation, and other applications. Compared to traditional internal combustion engines, hydrogen engines exhibit significant differences and advantages in combustion processes and emission characteristics. In-depth research into the combustion and emission characteristics of hydrogen engines holds significant practical importance for optimizing engine performance, enhancing energy utilization efficiency, and reducing environmental pollution. In recent years, numerous research teams worldwide have conducted extensive and in-depth studies on hydrogen engines, yielding a series of valuable outcomes that have propelled the continuous advancement of hydrogen engine technology. Examples include: High-Frequency Ignition (HFI) systems [1], ICE exhaust aftertreatment systems [2], and hydrogen fuel sensing technology [3].

Zero Carbon Emissions: Hydrogen combustion primarily produces water vapor, achieving zero carbon emissions throughout its entire lifecycle and thus helping to mitigate the greenhouse effect. Reduced Pollutants: Hydrogen emits almost no harmful gases, significantly lowering emissions of pollutants such as nitrogen oxides and improving air quality. High Strategic Energy Value: Hydrogen promotes energy diversification, facilitating the transition of energy structures from fossil fuels to a more varied mix and thereby enhancing energy security. Utilization of Renewable Energy: Hydrogen can be produced from renewable sources, promoting clean energy consumption and enabling sustainable energy development. Outstanding Technical Advantages: Hydrogen enables efficient energy conversion with high mass and energy density, rapid combustion speed, and enhanced engine thermal efficiency. Leveraging existing industrial infrastructure allows for development based on mature internal combustion engine technology, reducing R&D costs and accelerating commercialization. Long-term reduction in reliance on fossil fuels decreases fuel costs in the transportation sector. Driving industrial upgrading stimulates the hydrogen energy industry chain, creates new employment opportunities, and promotes economic transformation. By enhancing international competitiveness, hydrogen secures a leading position in technology and bolsters national scientific, technological, and industrial strength. Research on hydrogen engines is vital for environmental protection, energy security, technological innovation, and economic development, serving as a key pathway for sustainable progress.

This paper examines hydrogen engines from four perspectives: combustion characteristics, emission properties, engine structure, and material compatibility.

2. Combustion characteristics of hydrogen engines

2.1. Hydrogen blended combustion

The instability of hydrogen combustion means pure hydrogen burners remain some distance from commercialization. Simultaneously, novel hydrogen combustion technologies are not yet mature and require further development and promotion. Therefore, leveraging the currently advanced natural gas transmission pipeline network and established natural gas combustion technology, natural gas blended with hydrogen combustion represents one of the most practical and feasible development directions in the field of hydrogen combustion at present [4]. China remains in the R&D phase for hydrogen-blended combustion technology, with large-scale industrial applications yet to be widespread. Research on combustion and emission characteristics under full hydrogen blending ratios across the entire flame tube of gas turbine annular combustion chambers is scarce.

Hydrogen-blended natural gas combustion increases temperatures within the flame tube, concentrating the high-temperature zone. However, the cooling effect from the blending orifice minimizes the impact on exit temperatures. When the hydrogen blending ratio is below 0.6, the temperature distribution at the flame tube outlet becomes more uniform as the blending ratio increases. However, when the blending ratio exceeds 0.8, the average outlet temperature rises significantly, and the temperature distribution becomes more concentrated. Simultaneously, due to hydrogen blending, combustion occurs earlier, increasing the high-temperature zone near the nozzle. This can cause erosion at the inlet nozzle, leading to component failure.

Regarding combustion product emissions, blending hydrogen with natural gas reduces CO and CO_2 emissions, contributing to lower carbon emissions. However, hydrogen blending also increases

H_2O production, which further affects the distribution of combustion products and the combustion process within the combustion chamber [5].

2.2. Abnormal combustion phenomena and suppression

Due to hydrogen's combustion characteristics, attempting to construct the mixture formation and combustion of a hydrogen internal combustion engine based on traditional internal combustion engine theory leads to abnormal combustion—a major bottleneck for hydrogen engines. The most challenging abnormal combustion phenomena are pre-ignition, detonation, and backfiring. Premature ignition and detonation occur when hydrogen spontaneously ignites at a hot spot before or after spark plug ignition. This phenomenon is a primary reason hydrogen cannot be directly used in conventional internal combustion engines. Hydrogen's minimum ignition energy (0.02 mJ) is significantly lower than gasoline's (0.25 mJ), enabling hydrogen engines to burn lean mixtures while ensuring rapid ignition. The low ignition energy also allows localized high-temperature points within the cylinder to become ignition sources, triggering spontaneous combustion.

The high gas temperature inside the hydrogen internal combustion engine cylinders aids in increasing gas pressure and boosting output power. However, excessively high temperatures can cause pre-ignition, detonation, and backfiring issues. They also lead to elevated exhaust temperatures, significant thermal energy loss, severe thermal damage to internal cylinder components, and increased NOx concentrations. Therefore, controlling overheating during hydrogen internal combustion engine operation is critical.

Under high compression ratios and heavy loads, elevated cylinder temperatures readily create hot spots that trigger pre-ignition. Pre-ignition causes phase misalignment across all four strokes, resulting in reduced engine efficiency and unstable operation. Premature ignition also readily triggers backfires, particularly pronounced in external-mix hydrogen internal combustion engines with intake manifold injection. While hydrogen's low ignition energy, broad ignition limits, short flame quenching distance, rapid flame propagation speed, and high cylinder pressure rise rate are advantageous for power output, these characteristics also make premature ignition issues significantly more severe in hydrogen engines compared to conventional internal combustion engines. The primary reason for the limited adoption of port-injected hydrogen internal combustion engines is the abnormal combustion issues such as pre-ignition, backfiring, and detonation [6].

Simultaneously, knock intensity increases with the mass fraction of unburned mixture, being closely related to mixture concentration.

Therefore, primary methods for suppressing knock in direct-injection hydrogen engines include: optimizing combustion chamber design to avoid structures prone to generating or retaining hot spots (e.g., omega chambers), and optimizing nozzle placement to prevent narrow gap spaces. Optimizing injection strategies, where appropriately advanced injection enhances mixture homogeneity and reduces knock risk. However, excessive advance may cause hydrogen diffusion and accumulation within the nozzle or spark plug gap, potentially triggering knock. Employing EGR and water injection to lower in-cylinder combustion temperatures and suppress knock. Utilizing boost technology to enable lean-burn operation under equivalent load conditions, thereby raising the knock boundary [7].

3. Emission characteristics of hydrogen engines

3.1. Analysis of primary emissions

Hydrogen contains no carbon elements. Theoretically, exhaust from hydrogen engines should not contain harmful pollutants such as HC or CO. However, lubricant consumption during engine operation results in minor HC and CO emissions [7].

Under normal combustion conditions, hydrogen engines exhibit low carbon monoxide emissions. This is because hydrogen combustion primarily produces water and trace nitrogen oxides, theoretically eliminating carbon monoxide generation. However, incomplete combustion scenarios—such as excessively rich mixtures or low combustion temperatures—may result in minor carbon monoxide formation. When the mixture is too rich, insufficient oxygen prevents complete hydrogen combustion, causing partial hydrogen to undergo incomplete oxidation and form CO. During low-load operation or cold starts, lower combustion chamber temperatures slow chemical reaction rates, potentially increasing CO production.

3.2. Technical measures to reduce emissions

At low engine speeds and loads, piston and cylinder liner deformation is minimal, allowing piston rings to effectively collect lubricating oil from cylinder walls. Simultaneously, the low peak combustion pressure within the cylinder helps maintain the boundary film layer in the combustion chamber. These factors collectively result in lower HC and CO emissions during low-speed, low-load operation. Conversely, at high speeds and heavy loads, elevated combustion temperatures and peak pressures occur. Simultaneously, engine deformation increases relatively, leading to higher oil consumption and slightly elevated HC and CO emissions. The high-tension piston ring set 2 achieves tighter clearance with the cylinder bore, enhancing oil collection efficiency. Consequently, oil consumption decreases, enabling hydrogen engines to approach near-zero HC and CO emissions [8].

4. Key technical challenges of hydrogen engines

4.1. Engine structure

Hydrogen engines retain the fundamental structure of conventional engines, incorporating crankshaft-connecting rod mechanisms, valve train systems, and fixed components. Additionally, tailored to hydrogen fuel characteristics, enhancements are made to the fuel supply system, control and management system, combustion system, and specific components. Key additions include a dedicated hydrogen engine control system and a hydrogen supply system. The hydrogen supply system primarily comprises a hydrogen tank, pressure regulator, hydrogen filter, hydrogen pressure rail, hydrogen temperature sensor, hydrogen pressure sensor, hydrogen injection valve, and hydrogen supply line. Based on hydrogen injection location, hydrogen engines can be categorized into two types: external injection (external mixing) and direct injection (internal mixing). Direct injection engines further subdivide into pre-compression (low-pressure) injection and post-compression (high-pressure) injection [6].

4.2. Material compatibility

Among all hydride-forming alloys, titanium-based alloys have garnered significant attention due to their low molecular weight and high hydrogen storage capacity (up to 1.9 wt%). Typically, the desorption temperature of titanium hydrides exceeds 600°C. By combining titanium with transition group elements (e.g., Fe, Co, Cr, Ni, V) to form AB-type titanium-based alloys, this temperature can be reduced to near room temperature. A_2B alloys are compounds of alkaline earth metals (A) and transition metals (B). For example, Mg_2Ni is the most common A_2B alloy. Although elemental Mg possesses excellent hydrogen storage capacity (~7.6%), its desorption temperature is elevated due to the exceptionally strong and stable Mg-H bond in MgH_2, limiting its practical application. However, its stability can be adjusted by alloying with various metals—including transition metals (Co, Ni, Cu, Fe, Sc, Y, Ag), rare earth metals (La, Ce), and non-transition metals (Al, Li, etc.)—to suit practical applications [9].

Titanium-based alloys find extensive applications in the automotive industry, playing crucial roles in engine systems, suspension systems, exhaust systems, and vehicle body frames. Leveraging their exceptional heat resistance, these alloys are used to manufacture critical engine components like crankshaft connecting rods. This not only enhances vehicle fuel efficiency by conserving fuel or electrical energy but also significantly improves engine fatigue resistance. Due to their relatively low elastic modulus, titanium alloys are also employed in automotive elastic components. In exhaust systems, titanium-based alloy exhaust pipes can last up to 13 years—twice the lifespan of traditional steel pipes—while offering approximately 8kg in weight reduction. Additionally, titanium alloys are suitable for half-shafts and fasteners in new energy vehicles [10].

5. Future development trends

Despite rapid technological advancements in hydrogen production and storage, injecting liquid hydrogen into engines at ambient temperatures remains challenging. Consequently, ongoing research is needed to enhance the performance and emissions of port-injected hydrogen engines. Achieving industrial-scale manufacturing requires further optimization of all engine characteristics. Current strategies for intake manifold hydrogen injection engines are limited, and most R&D institutions show reduced enthusiasm for developing such engines. For direct-injection hydrogen engines, research should primarily focus on analyzing hydrogen cylinder injection and internal combustion processes, providing a theoretical foundation for developing cylinder flow schemes for this engine type. Leveraging the multiple advantageous characteristics of liquid hydrogen injection, laboratory-scale analysis and exploration of liquid hydrogen injection should be conducted. This approach ensures continued applicability even as hydrogen supply systems mature. Commercial vehicles such as heavy-duty trucks and buses should serve as breakthrough points for establishing diesel-to-hydrogen conversion demonstration projects. China's hydrogen energy application in transportation remains in its infancy, with hydrogen refueling infrastructure still underdeveloped. Commercial vehicles, however, operate within relatively fixed application scenarios and routes, significantly reducing dependence on hydrogen refueling infrastructure. Fuel cells' high power output and diesel replacement capabilities are well-suited for commercial vehicle applications, where hydrogen refueling challenges can be effectively addressed. Building upon large-scale demonstration projects for commercial vehicles, comprehensive hydrogen refueling infrastructure coverage can be gradually achieved, thereby driving the adoption of hydrogen technology in passenger vehicles.

6. Conclusion

Hydrogen combustion exhibits rapid flame propagation, and the temperature rise from combustion has a more pronounced effect than the pressure rise, leading to elevated NOx emissions. Therefore, it is essential to suppress temperature rise without compromising pressure effectiveness. The rapid temperature rise during hydrogen compression and its low minimum ignition energy are the primary reasons hydrogen internal combustion engines are more prone to abnormal combustion phenomena such as pre-ignition. Abnormal combustion can also occur under high-temperature, high-pressure conditions, though methods exist to suppress phenomena like detonation. Currently, hydrogen-blended combustion holds significant development potential. Existing natural gas transmission networks and mature natural gas combustion technologies pose no issues, but progress is still constrained by hydrogen transportation, storage, and combustion technologies.

Hydrogen contains no carbon. Carbon-containing gaseous pollutants primarily result from incomplete combustion within the engine. Consequently, the emissions of such pollutants remain low. By modifying the combustion chamber environment, optimizing the design of pistons and cylinder liners, and improving the effectiveness of piston rings in collecting cylinder wall lubricating oil, emissions of carbon-containing gaseous pollutants can be reduced. This enables hydrogen engines to achieve near-zero emissions of carbon-containing pollutants.

Hydrogen engines retain the fundamental structure of conventional engines while incorporating numerous additional components, including hydrogen engine control and supply systems. Regarding hydrogen storage materials, titanium-based alloys offer excellent hydrogen storage capacity and are widely used in the automotive industry. They exhibit outstanding heat and fatigue resistance and are lighter than traditional steel materials.

Hydrogen internal combustion engines directly combust hydrogen, enhancing efficiency through optimized combustion chamber design, ignition systems, and injection technologies (e.g., high-pressure direct injection, lean-burn combustion). Challenges such as backfiring, pre-ignition, and NOx emissions still need to be addressed. The technical barriers are relatively low, and these engines can be partially integrated with existing internal combustion engine architectures.

With technological advancements and the continuous maturation of hydrogen engine technology, the hydrogen energy industry holds vast potential for development.

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