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Advanced hydrogen engine for modern transportation industry

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Abstract. Numerous environmental issues, such as climate change brought on by the greenhouse effect, result from the expanding air transportation sector. The internal combustion engine industry faces enormous difficulties due to the dual pressures of energy conservation and environmental protection, making finding new clean energy sources essential. To combat global warming, there is growing interest in achieving carbon-neutral flight. As the globe looks for new solutions to combat climate change and global warming, renewable energy and hydrogen have emerged as the environmental sectors' saviors. One of the key energy vectors for the twenty-first century is hydrogen. Particularly in the transportation industry, hydrogen as an energy carrier has the potential for sustainable development. Compared to other internal combustion engines, a hydrogen-fueled engine has the potential to produce significantly cleaner emissions. Based on the prediction of its future development direction, this paper focuses on the latest advances and challenges of the hydrogen engine, analyzes and summarizes the current research status of the hydrogen engine, and looks forward to its future development.

Keywords: climate change, internal combustion engine, hydrogen engine, transportation industry.

1. Introduction

Due to the planet's expanding population and the excessive consumption of fossil fuels, the world's requirement for energy generation has considerably expanded in the twenty-first century. By 2021, the total global oil consumption, which was 3928 million tons in 2008, is predicted to increase to 5300 million tons. But oil is a limited resource that is getting harder to find and more expensive. Fossil fuels currently supply 65% of the world's energy needs because they are readily available. A sizeable portion of this energy is used by machinery and vehicles, which depend on fossil fuels for operation. Around the world, 1.42 billion cars and light trucks were used in 2018 (Figure 1). More than 2 billion cars are expected to be on the road by 2050 [1].

An energy crisis (fuel shortage) has resulted from the fall in fossil fuel supply. On the other hand, due to their versatility, internal combustion (IC) engines will continue to rule the power and transportation sectors [2]. IC engines release pollutants that harm the atmosphere and lead to severe issues like global warming, air pollution, acid rain, and respiratory issues. The quickest possible development of "clean-burning" fuels produced from renewable sources is required to guarantee IC

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engines' long-term security and viability. In this regard, efforts have been undertaken to increase engine energy efficiency and conduct research on the usage of sustainable and renewable alternative fuels [3].

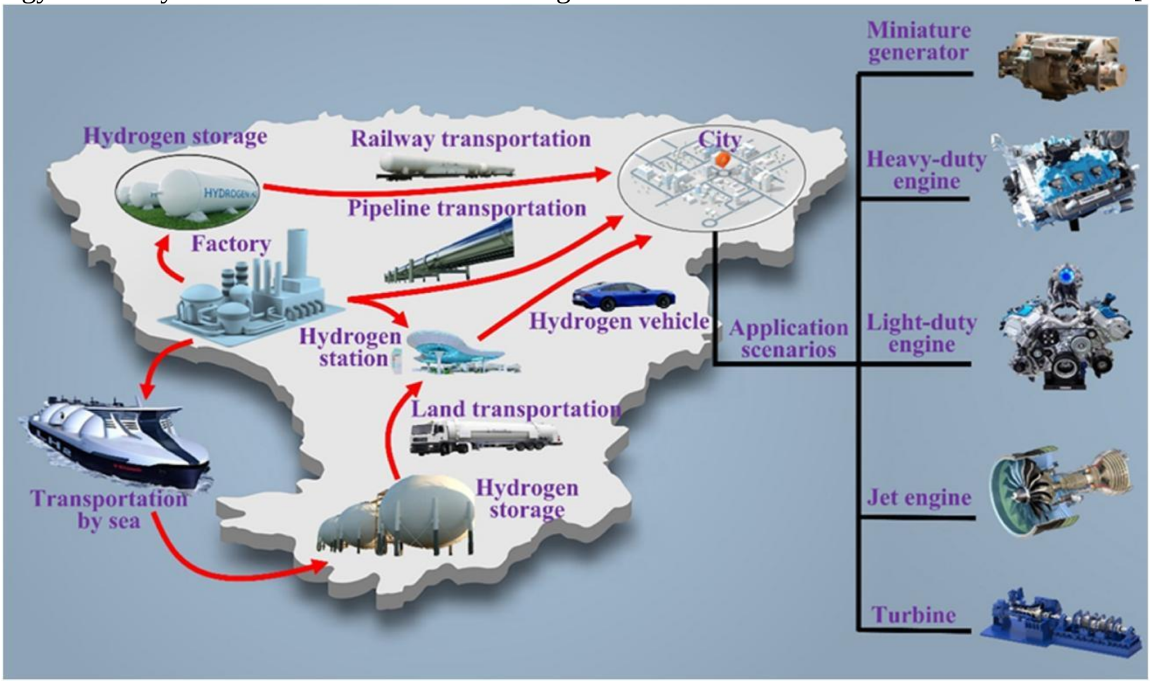

Figure 1. The route of hydrogen storage, transportation, and application [6].

Hydrocarbon fuels have been a key component of propulsion and power production for over a century. Nonetheless, tighter environmental rules on exhaust emissions and the expectation that global petroleum sources will run out strongly promote research into alternate fuels [4]. Conversely, according to most energy policy experts, using hydrogen as a fuel for internal combustion engines rather than fuel cells is more likely to happen in the transportation sector for at least a few decades. Although several obstacles still stand in the way of using hydrogen as a fuel in the transportation industry, current research on hydrogen generation, delivery, and storage has produced some encouraging results [5].

2. Mechanism and unique characteristics of hydrogen combustion engine

Hydrogen needs the correct amount of oxygen and ignition energy to ignite, just like other fuels do. Yet, hydrogen is more energetic and ignites with less energy. An engine that runs on hydrogen may be utilized similarly to traditional internal combustion regarding energy conversion. The fuel mixture is ignited, causing it to heat and spread in the combustion process, causing the piston to move. The fuel mixture then turns the motion of the piston into mechanical energy, which is subsequently output externally by rotating the crankshaft via the crank linkage [6]. As can be seen, a hydrogen engine operates exactly like a conventional internal combustion engine; hydrogen substitutes for conventional fossil fuels, but due to the differences between hydrogen and gasoline and diesel, the engine must be adjusted appropriately to complete the typical working cycle.

Hydrogen has several advantages over diesel and gasoline, including a high mass calorific value, rapid combustion, high diffusivity, a broad range of combustible concentrations, zero pollutant emissions, and superior anti-explosive properties. Only nuclear fuel has a greater calorific value when burned, proving hydrogen's superiority as an energy source. Due to hydrogen's strong diffusivity, the mixture benefits from uniform concentration, quick mixing, and circumstances that approach fixed-volume combustion. These elements all improve combustion efficiency.

Fuel having no carbon content, hydrogen, is very effective. One of the primary disadvantages of hydrogen is that it emits substantially less hazardous exhaust pollution than fossil fuels and has a heating value three times that of petroleum in fuel cells and internal combustion engines. One of hydrogen's main benefits is that it only emits water when utilized in a fuel cell, making it an ecologically benign fuel. Hydrogen has a heating value of 4, 2, and 2.4 times higher than coal, gasoline, and methane. Compared to fossil fuels, the most common element, hydrogen, has the highest specific energy content [7]. Because hydrogen has a far higher diffusion coefficient than gasoline, the mixture of air and fuel is more homogeneous. When hydrogen is injected, its flammability ranges widely, making it simpler to run engines under lean circumstances. Additionally, hydrogen is best adapted for SI engines than compressed ignition (CI) engines due to its greater combustion temperature.

The performance and exhaust emissions of a gasoline engine can be enhanced by hydrogen due to its numerous favorable properties. Ceviz et al. investigated how modest amounts of hydrogen added to gasoline-air mixtures affected the efficiency and exhaust combustion characteristics of an engine with spark ignition. The four potential air-fuel ratios range between 0% through 2.14%, 5.28%, and 7.74% by volume. In addition to improving engine performance characteristics like thermal efficiency and specific fuel consumption, increasing the air-fuel ratio has the potential to reduce CO and HC emissions dramatically. Li et al. indicated that introducing hydrogen to an engine reduced the combustion delay time, reducing fuel consumption [8].

Table 1. Different characteristics of hydrogen, gasoline, and diesel [7].

Properties	Hydrogen	Gasoline	Diesel
Carbohydrate content (mass percent)	0	84	86
Molecular mass	2.015	110	170
A/F stoichiometric ratio	34.3	14.6	17
Temperature of ignition (K)	858	530	-
Temperature of adiabatic flame (K)	2384	2270	2300
293 K (cm/s) flame speed	237	41.5	-
Flammability limits (vol percent in air)	4.1–75	1.5–7.6	0.6–5.5
Quenching the gap (cm)	0.06	0.2	-
Lower heating value per kilogram (MJ/kg)	120	44	-
Diffusion coefficient (cm^2/s) under stoichiometric conditions	0.61	0.05	-

3. Latest advances in hydrogen engine

3.1. Hydrogen-blended gasoline engines

Researchers have been working on hydrogen-blended gasoline engines since scientists first studied them. Eventually, the technology needed to make these engines emerged quite quickly. Encouraging advancements have also been achieved in gasoline engines that use hydrogen-blended fuel, especially in the last 20 years.

Reciprocating piston petrol engines are spark-ignition engines that use precisely adjusted hydrogen and gasoline fuel mixes for various engine operating circumstances. H_2 is required to improve hydrocarbon fuels' combustion, physio-chemical, and ignition properties. But hydrocarbon gasoline engines may exceed ordinary gasoline engines in terms of performance. Proper lean combustion is a good way to improve engine performance. Since hydrogen has a broad fire limit range and excellent lean combustion features, hydrocarbon petrol may operate at much lower pressures. It is critical to emphasize that one of the challenges to the commercialization of hydrogen engines is hydrogen injectors. Currently, hydrogen is directly injected into the cylinder via low-pressure gasoline or CNG nozzles. However, the injectors' lifespan is limited due to attrition and poor maintenance. Despite substantial research on hydrogen engines' combustion and emission performance, only a few Chinese experts have undertaken an in-depth study on hydrogen nozzles. Hydro nozzles must be thoroughly investigated since they will decide if hydrogen engines are economically viable.

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Because they have fewer parts and components, rotary engines are more compact and operate with less vibration than typical reciprocating piston engines. The mechanical layout of rotary engines also provides improved performance at faster speeds and larger power densities in addition to these features. Rotary engines have several drawbacks over reciprocating piston engines, including limited power production at low speeds, seal difficulties, poor mechanical efficiency, and greater CO and HC emissions. Hence, in actual applications, the two major difficulties with rotary engines are minimizing harmful emissions and boosting fuel efficiency. Gasoline-powered rotary engines need fuel with a quick flame speed and simple evaporation due to their large combustion chambers and high operating speeds. The aforementioned obstacles may be overcome due to hydrogen's high diffusivity and fast flame velocity. Fuel efficiency, emissions, and operational performance of gasoline rotary engines are all adversely affected by combustion chamber anomalies. Enhancement of the combustion process with the addition of H_2 is a useful technique to stop the engine's performance from degrading under varied operating situations, notably at idle. Although being researched, the rotary engine only has a few uses. Moreover, the rotary engine has drawbacks such as mechanical losses, poor thermal efficiency, and gas leaks. Hydrogen can help the rotary engine's shortcomings, but the traditional piston engine must still be employed.

3.2. Hydrogen-blended diesel engines

Because of their low fuel consumption and strong power output, diesel engines are extensively used in heavy and medium-duty vehicles. Although having the aforementioned properties, their application is limited by severe drawbacks such as excessive soot and nitrogen oxide emissions. The application of hydrogen-diesel combination fuel will drastically cut carbon-based emissions while also improving the efficiency of diesel engines. Additionally, because hydrogen has a wider spectrum of combustibility, the engine can operate at extremely low equivalence ratios, and hydrogen's rapid diffusion and flame speed drive a variety of combustion in the cylinder.

Due to hydrogen's special characteristics, diesel engines' combustion process may be further optimized by ensuring a more uniform mixture of fuel and air. Also, it could improve diesel engine efficiency and lessen the detrimental effects of EGR. Aldehyde, alkene, alkyne, cyclic hydrocarbons, and other hydrocarbon species prevalent in diesel engine emissions are considered particularly dangerous; addition may lessen these negative emissions. Diesel engines offer various benefits over gasoline engines, including no throttle, high compression ratio, and direct diesel injection. The air displacement in the intake manifolds will negatively impact the performance of diesel engines, even though adding hydrogen to diesel engines can greatly reduce harmful emissions. Diesel engines with a hydrogen mix may knock due to a high compression ratio; however, research on this topic is scarce. Also, scientists ought to pay closer attention and provide solutions for the higher NO_x emissions that result from the addition of hydrogen. An excellent option would be a NO_x storage reduction (NSR) or selective catalytic reduction (SCR) catalytic system. Further research should focus on the use of the after-treatment technology and the combustion and emissions performance of the engines.

The most prevalent internal combustion engines today are gasoline and diesel. The introduction of hydrogen to gasoline and diesel engines offers many benefits and drawbacks. An optimal hydrogenation ratio must be determined based on the loads and operating circumstances to optimize the advantages of hydrogenation in terms of improved performance and reduced emissions.

3.3. Hydrogen-blended natural gas engines

Natural gas (NG) engines still have performance issues, such as a high chamber coolant valve (CCV) and a poor lean combustion capability, despite significant energy efficiency and pollution reduction improvements. Researchers are paying more and more attention to hydrogen-blended natural gas engines due to the great properties of hydrogen. Research on natural gas engines with hydrogen as a blend has also accomplished some progress.

Because of their higher ignition temperature and slower laminar burning velocity, NG motors possess poor lean-burn capacity. Moreover, mixing natural gas with hydrogen might be a workable option for the concerns above. Furthermore, although raising engine speed at a lower capacity level was demonstrated to prolong the slim and effective limit, boosting engine speed at a high load level had no effect within the extension limit. Because of its high initiating energy and low laminar burning velocity, the NG engine is substantially more prone to CCV. Lean combination circumstances or high dilution mixes worsen the problem. Adding H_2 and enhancing ST may increase hydrogen-blended NG engines' performance, efficiency, emissions, and lean-burn capability. Natural gasoline engines perform badly as low-polluting and economical engines than typical fossil fuel engines. Unlike what consumers want, natural gas engines' power output would progressively decline, even though adding hydrogen to them could boost fuel efficiency and eliminate dangerous emissions and cyclic fluctuations.

3.4. Hydrogen-blended alcohols engines

Since methanol, ethanol, and n-butanol are renewable fuels, they enable smokeless combustion and lower NO_x emissions in their engines. Yet compared to gasoline, alcohol has worse fuel vaporization and diffusion properties, which might lead to diminished charge homogeneity and inadequate combustion, which are both bad for the engine's performance in terms of efficiency and emissions. Hydrogen-blended alcohol engines should resolve the above issues due to the exceptional properties of hydrogen.

Alcohols are now being got to add to fossil fuels more often. The bad cold start performance for alcohol engines is one of the main obstacles to their development. Future research may concentrate on creating a complete and effective combustion strategy focused on hydrogen addition to addressing the problematic cold starts of alcohol engines rather than examining the performances of hydrogen-blended alcohol engines. [9].

4. Main challenges and opportunities

The unexpected hydrogen fuel characteristics, as previously noted, might harm certain fuel injection system components. A reliable and accurate injection capability is required for direct hydrogen injection. A fuel nozzle's cylindrical needle tip/seat contacts surface experience impact wear. Because of the impacts between the injector needle and the fuel outlet socket as it opens and closes, these components are vulnerable to impact wear. In real life, the sliding impact may be observed through the contact between the needle and the seat when it comes in contact with the nozzle. As a result, some energy is lost just at the injector's needle or nozzle seat contact sites. The plastic contact area between the nozzle seat and needle face deforms slightly during a break-in. This will carry on until equilibrium is achieved. Because of the nozzle hole's exact cylindrical surface, the injector needle might well be directed.

Many factors have an impact on the friction properties, technique, as well as wear of metal components. The main factors are the material's mechanical and thermochemical processing, the workplace environment, lubrication, and the development of surface oxide layers. The steady loss of surface oxides caused by wear will bring the surface into contact with the bare material in the chemically reducing hydrogen environment. As a result, friction and wear are increased. Before the piezoelectric stack's epoxy coating delaminates, air bubbles can also exhibit degradation indicators. According to the earlier study, the epoxy substance is prone to hydrogen diffusion. As pressure is released, decompression damage occurs. Additional effects of epoxy degradation include carbon tracks, holes, and micro-arcing. This might lead to an electrical issue between neighboring electrodes in the stack, leading to an inner short circuit.Furthermore, because hydrogen seeps into the material's lattice, piezoelectric components are vulnerable to hydrogen contact. As a result, the development of -OH bonds modifies the crystal's internal dipole moments, degrading the material's electrical characteristics. Corona discharges can harm piezoelectric material surfaces.

Due to the poor lubricating qualities of hydrogen and wear on the injector components, some hydrogen regularly escapes into the engine's combustion chamber. An engine may stall if these leaks result in aberrant combustion processes like knocking and flame back. Moreover, the liquid hydrogen fuel pump's breakdown might be caused by gas creation in the compression chamber generated by the pump piston and cylinder. The pump fails due to its inability to perform properly due to hydrogen gas

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generation. At the fuel tank, where the pump is placed, the saturated liquid hydrogen is quickly converted into gaseous hydrogen. Despite this, friction generates just a little quantity of heat. The moving piston may also readily cause friction. Since friction increases with delivery pressure, it is critical to keep it at or below zero [10-12].

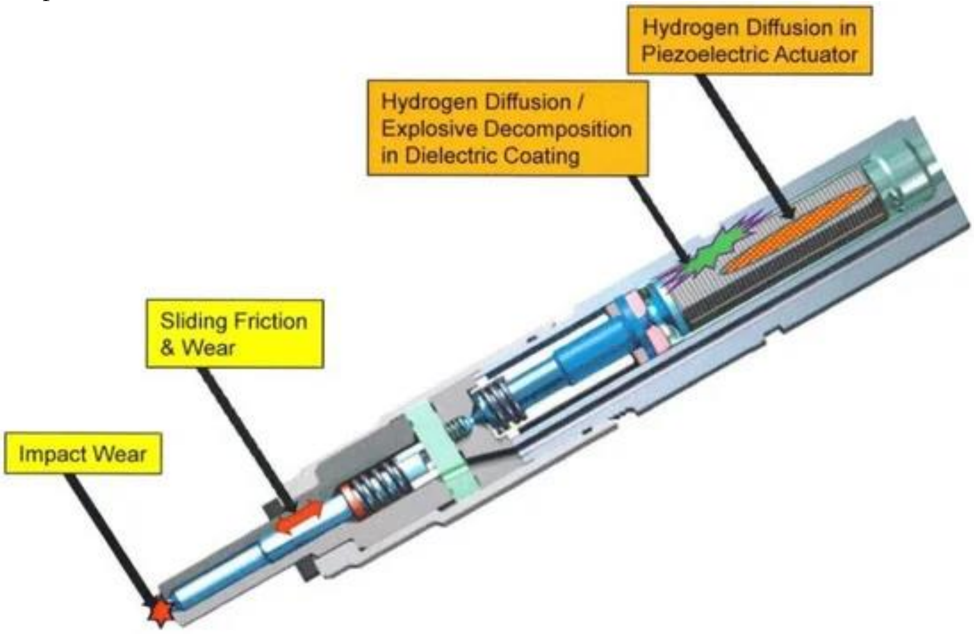

Figure 2. Areas and types of fuel injector damage [10].

5. Conclusion

The search for alternative fuels is driven by growing concern about the global and economic repercussions of potential oil supply shortages and the desire to minimize emissions of greenhouse gases in the transportation sector, which is a core component of our global world built on transportation. Hydrogen is now developing into a renewable power sector in addition to its conventional utilization as a raw material in manufacturing methanol and ammonia. The methods utilized to produce hydrogen using traditional and alternative sources of energy, and the way it is used, stored, transported, and distributed, are covered in great length in this study. It also discusses the major challenges associated with developing such systems. Hydrogen may be produced using sun, windy, geothermal, hydropower, biofuel, and other renewable energy sources. Hydrogen seems to be the greatest material to employ as a fuel, energy carrier, and storage medium due to the potential for fluctuating renewable energy sources like the sun and wind. The use of hydrogen as a fuel and alternative energy carrier is becoming increasingly widely recognized globally due to its benefits and the accessibility of carbon-free substitutes. The advantages of hydrogen fuel are significant, but there are also disadvantages. Problems such as abnormal combustion, stable production of green hydrogen, large-scale storage and transportation, and the cost of container materials are obstacles to the industrial application of hydrogen engines and hydrogen energy, in addition to the lack of systematic standards for the safe use of hydrogen energy, so the research work on hydrogen fuel engines and new materials and the construction of infrastructure need to be carried out quickly.

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