Hydrogen Fuel Internal-Combustion Engines

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To achieve the goals of low carbon emission and carbon neutrality, some urgent challenges include the development and utilization of low-carbon or zero-carbon internal combustion engine fuels. Hydrogen, as a clean, efficient, and sustainable fuel, has the potential to meet the abovementioned challenges. Thereby, hydrogen internal combustion engines have been attracting attention because of their zero carbon emissions, high thermal efficiency, high reliability, and low cost.

hydrogen internal combustion engine   high efficiency   low NOx emission

1. Opportunities for Hydrogen Internal-Combustion Engines

Environmental issues and global warming have become more prominent and critical in the past few decades. To solve these problems, the Paris Agreement reached a consensus and decided to attempt to slow the progress of global warming processes in December 2015, the goal of which being to control the increasing global rising temperature to within 2 °C in the 21st century. Therefore, many countries have been proposing and implementing carbon-reduction and carbon-neutrality strategies. At the 75th session of the United Nations General Assembly (September 2020), China proposed a double carbon target of peaking carbon dioxide emissions by 2030 and achieving carbon neutrality by 2060 and introduced a series of policies to promote the process of carbon reduction, creating a strong demand to decarbonize not only transport sectors, but also the power industry, incentivizing away from conventional carbon-based fuels and towards renewable energy sources. Hydrogen can be produced from several varieties of renewable energy sources and efficiently obtained through large-scale electrolysis. And after its reaction with oxygen, water is produced. Additionally, hydrogen combustion or electrochemical reactions can be used to generate thermal or electric energy as power sources for cars. Although hydrogen is less portable and has a lower volumetric energy density than liquid fuels, it has proven itself as having the highest mass-specific energy density among general fuels, such as gasoline, diesel, methanol, ethanol, and so on.

Up until now, hydrogen has been bridging the low-carbon economy and renewable energy, which suggests its key role in preventing global warming. Many countries have begun to produce hydrogen. According to the International Hydrogen Energy Commission's statistics, 228 projects in the global hydrogen energy industry chain have been built, and more than 20 countries and regions, such as the United States, Japan, the European Union, South Korea, and New Zealand, have issued hydrogen energy-development strategies [1]. In December 2021, China's Ministry of Industry and Information Technology issued the Industrial Green Development Plan, a proposal to accelerate hydrogen energy technology innovation and infrastructure construction and promote the diversified use of hydrogen energy.

At present, the use of hydrogen energy in the power vehicle industry mainly includes fuel cells and internal-combustion engines. Hydrogen fuel cells are high-efficiency electrochemical devices that directly convert chemical energy into electric energy and only produce water as a by-product without any other harmful emissions. However, hydrogen fuel cells have a disadvantage in terms of their cost and service life, and the prices of fuel cell vehicles are still much higher than those of traditional vehicles [2]. Based on the abovementioned reasons and combustion characteristics of hydrogen, it is attractive as a fuel for internal-combustion engines. Extensive literature studies have shown that hydrogen, as a fuel for internal-combustion engines, has a wider flammable range, the ignition limit range of which expressed by the air–fuel ratio is 0.14 to 10, the minimum ignition energy required is one-tenth of that of gasoline fuel, and the laminar flame velocity is more than six times faster than that of conventional fuels. Hydrogen also has a higher diffusion coefficient, lower ignition energy, and wider flammability limit, which, when compared with conventional fuels, result in better heat and mass-transfer characteristics, better lean-burn characteristics, and lower misfire rates, as can be seen in **Table 1** [3][4][5][6].

Table 1. Physical and chemical properties of the different fuels [3][5][6][7][8].

Fuel Characteristics		Gasoline	Diesel	Methane	Hydrogen
Condition (normal temperature and pressure)		liquid	liquid	gas	gas
Atomic ratio	C	85	86	75	0
	H	15	14	25	100
	O	0	0	0	0
Density (kg/m^3)		720–780	830–855	0.65	0.071
Mass diffusivity in air (cm^2/s)		0.005	-	0.16	0.61
Lower heating value (MJ/kg)		44.5	42.5	55.5	120
Auto-ignition temperature (°C)		228–541	210	540	585
Flashpoint (°C)		−45	62	−188	−231
Minimum ignition energy (mJ)		0.24	0.24	0.29	0.02
Flammability limits (Lambda)		0.4–1.4	0.5–1.3	0.7–2.1	0.14–10
Stoichiometric air-to-fuel ratio (kg/kg)		14.7	14.3	17.24	34.2
Laminar burning velocity (m/s)		0.37–0.43	0.37–0.43	0.37–0.43	2.65–3.25
quenching distance (cm)		0.2	-	0.203	0.064

The lower heating value of hydrogen is much higher than that of gasoline and natural gas. Combining faster laminar flame speeds, lean-burn characteristics, and higher spontaneous combustion temperatures makes hydrogen internal-combustion engines have a high thermal efficiency and potential knock resistance. Hydrogen has a shorter quenching distance, which is about one-third that of gasoline and methane. This affects crevice combustion and wall-heat transfer [3]. In addition, the wide flammability limit enables hydrogen-fueled SI engines for quality control such as diesel engines, rather than volume control at fixed fuel–air mixture conditions close to stoichiometric ratios, as is the case in regular gasoline engines. This ensures that hydrogen engines have a higher indicated thermal efficiency than gasoline engines [9][10][11].

Compared with fuel cells, hydrogen internal-combustion engines can take advantage of the mature industrial chain and technology of existing internal-combustion engines, and only need to optimize the fuel supply and injection system, turbocharger matching, lubrication system, and crankcase ventilation [12]. Moreover, the purity of hydrogen is not strictly required; the byproduct of industrial hydrogen can be used, resulting in a lower user cost while fuel cells need high-purity, hydrolyzed hydrogen at the current stage and the cost is relatively high. Thus, hydrogen is an ideal alternative fuel for internal-combustion engines, which, in turn, assists the optimization and development of new energy technologies with hydrogen internal-combustion engines.

2. Research on Performance Improvement of Hydrogen Internal-Combustion Engines

Companies such as BMW and Ford Motor have been developing hydrogen fuel internal-combustion engine vehicles, and they have successfully demonstrated their excellent performance in terms of emissions and fuel economy [13][14][15][16][17]. BMW tested a specially designed engine with an external and internal mixture formation system to study the effect of different injection strategies on hydrogen engine performance [13][14]. The experimental results showed that the hydrogen engine, combining the external and internal mixture formation systems, can operate efficiently under partial load and lean-burn conditions. Stoichiometric mixture can be achieved even when operating at full load through external mixture formation or direct injection. For BMW’s operating strategy with a post-treatment catalyst to reduce emissions, using the lean mixture is only suitable for low-load engine conditions, while the stoichiometric mixture is suitable for high-load engine conditions. The average indicated pressure of the engine reached 1.8 MPa at 4000 rpm engine speed, which is higher than that of the basic gasoline engine.

A test for two BMW Hydrogen 7 Mono-Fuel demonstration vehicles was completed in 2008 [15]. The two vehicles were tested at the FTP-75 cold-start as well as the highway drive cycle, respectively, achieving fuel economy performances of 3.7 kg of hydrogen per 100 km on the FTP-75 cycle and 2.1 kg of hydrogen per 100 km on the highway cycle. These results are, respectively, equivalent to 13.8 L per 100 km and 7.8 L per 100 km for gasoline fuel consumption at the FTP-75 cold-start and highway drive cycle. These emission results on the FTP-75 cycle showed that emission levels are inferior to 0.0008 g/mile of nitric oxide (NOx) emissions, 0 g/mile of nonmethane hydrocarbon (NMHC) emissions, and 0.003 g/mile of carbon monoxide (CO) emissions. These emission results are equivalent to the Super Ultra Low Emissions Vehicle (SULEV) emission levels, which are 3.9% NOx, 0% NMHC, and 0.3% CO.

Ford motor company built and tested the first production-ready vehicle, the P2000, with a hydrogen internal-combustion engine that could run without throttle on a lean mixture [16][17]. The research team of Argonne National Laboratory evaluated several direct-injection hydrogen mixture formation strategies to reduce NOx emissions and achieve a higher thermal efficiency of the engine. The group carried out engine experiments under the speed range of 1000~3000 rpm and the average effective pressure range of 0.17~1.43 MPa [18][19]. The results showed that the effective thermal efficiency (BTE) was more than 35% under about 80% of test conditions. There was a balance between wall-heat loss and other losses as a function of engine speed and load. Therefore, the peak effective thermal efficiency of 45.5% and NOx emission of 0.87 g/kW·h were obtained at 2000 rpm and BMEP of 1.35 MPa. However, NOx emissions increased with the increase in speeds and loads, which means that the mixture formation needs to be further optimized.

Due to the potential of hydrogen as a flexible energy carrier, the development projects of large hydrogen internal-combustion engines based on diesel engines have also begun to emerge in recent years. The group of National Traffic Safety and Environment Laboratory and Tokyo City University has developed a large (medium load) truck with a multi-cylinder, spark-fired, direct-injection hydrogen engine [20]. The engine was developed for the project based on a four-cylinder diesel engine with a displacement of 4.73 L. A low NOx emission (0.7 g/kW·h), IMEP of 0.85 MPa, and indicated thermal efficiency (ITE) of 41% were obtained under the adopted combustion control strategy and the engine operating conditions. The torque was about 20% lower than that of the base diesel engine. The torque deficit of the hydrogen engine can be improved by boosting the intake air, but it is necessary to avoid pre-ignition and knock.

In order to achieve sufficiently low NOx emissions, high thermal efficiency and high torque without any post-treatment conditions. A study on large-scale hydrogen internal-combustion engines for stationary power generation was conducted in the Renewable Energy Research Center, National Institute of Advanced Industrial Science and Technology, Japan [21]. Experimental studies were carried out by changing the piston design, adding a spark plug, and adding a direct-injection hydrogen injector on a single-cylinder diesel engine with a displacement of 1.3 L. In the absence of a post-treatment system, an extremely high EGR rate and intake boost with suitable hydrogen mixture formation strategies were used to achieve NOx emissions below 200 ppm. The ideal IMEP is above 1.35 MPa (140 Nm) at 1000 rpm, reaching the level of a benchmark diesel engine. Distinct from previous research on the injection strategy of the direct-injection hydrogen engine, it is proposed to set the injection pressure at a lower level through small-hole injection, which attempts to produce the stratification of the hydrogen mixture in the engine cylinder. Although low injection pressure and long hydrogen-injection time may lead to the increase in mixture inhomogeneity, there is a trade-off between the equivalent ratio and NOx emissions. In this study, lower NOx and higher ITE could be achieved when the global equivalent ratio was kept around 0.3. By analyzing the effect of EGR on combustion performance, it was found that the EGR rate had only a slight effect on combustion performance. No matter how large the EGR rate is, the indicated thermal efficiency, the average indicated pressure, as well as CA50 were essentially unchanged. However, increasing the EGR rate could significantly reduce nitrogen oxide emissions. In addition, it can be concluded that the inhomogeneity of the hydrogen mixture in the cylinder, results in robust combustion, which is not sensitive to the EGR rate. Experiments suggested that the maximum IMEP was 1.46 MPa, the engine NOx emission was less than 150 ppm, the boosting pressure was 175 kPa, the oxygen concentration of the intake air was 12.5 vol%, and the corresponding EGR rate was about 50%. To further improve IMEP and thermal efficiency without increasing NOx emissions, Atkinson/Miller cycles were used to attempt to delay the intake valve closing and exhaust valve opening to reduce the effective compression ratio and increase the effective expansion ratio. The IMEP eventually reached 1.64 MPa, NOx emissions were below 100 ppm, and the ITE was more than 50%.

In order to increase the power output and reduce NOx emissions, Verhelst's research group studied an in-cylinder direct-injection hydrogen internal-combustion engine equipped with EGR and a turbocharger under lean-burn and stoichiometric mixture conditions [22][23]. Comparing the performance of lean-burn without post-treatment and stoichiometric mixture conditions with both EGR and the post-treatment system, it was found that lean-burn combined with a turbocharger is the more effective method for achieving higher efficiency and lower NOx emissions. Clearly, to avoid abnormal combustion and unacceptable levels of NOx emissions, lean burns require higher boosting pressures for keeping the equivalent ratio enough low. Otherwise, lean-burn operation of the engine will inherently result in insufficient torque or power. On the other hand, a power output higher than 30% of gasoline can be achieved when selecting a supercharged stoichiometric mixture with EGR, but fuel economy is sacrificed by catalytic post-treatment with NOX removal.

By changing the hydrogen-injection timing, homogeneous mixture combustion, stratified combustion, and diffusion combustion can be realized in hydrogen internal-combustion engines. Toyota Motor Corporation conducted experimental research in a 2.2 L four-cylinder diesel engine equipped with a centrally mounted hydrogen injector, a toroidal shape combustion chamber, and a spark plug in the glow-plug position [24]. The research investigated the high efficiency and low NOx of hydrogen combustion using a prototype high-pressure hydrogen injector (maximum 30 MPa). In addition, stratified combustion and spark-assisted diffusive combustion was investigated, and the results showed that the pressure-recovery effect by injection close to TDC and EGR effectively combined with stratified and diffusive combustion by high-pressure direct injection greatly improved the indicated thermal efficiency by approximately 3% compared with conventional homogeneous combustion. Furthermore, suppressing jet penetration and reducing cooling loss, a 52% ITE was achieved for a small engine.

The Indian Institute of Technology research groups developed the stoichiometric or over-stoichiometric mixture-formation strategies, including cooled EGR, turbocharging, and NOx removal catalytic post-processing, to achieve higher torques and prevent abnormal combustion and high NOx generation [25]. Using unburned hydrogen as a NOx-reducing agent under stoichiometric conditions, a peak torque of 180 Nm was achieved at 3600 rpm with over 800 ppm NOx and a BMEP of approximately 0.9 MPa.

3. Port Injection and Direct Injection of Hydrogen

The hydrogen-injection methods of the hydrogen internal-combustion engine are divided into port fuel injection (PFI) and direct injection (DI) in the cylinder, but due to the small hydrogen density, the port injection will lead to a decrease in the intake efficiency, resulting in a significant decrease in power density. Direct injection in the cylinder can not only improve the intake efficiency and consequently result in a greater power density, but also avoid backfire compared with PFI, which can increase the power density by 38.4%. In addition, direct injection can also achieve a more flexible organization formation of the mixtures and, in turn, achieve a variety of combustion modes such as stratified combustion and homogeneous combustion or even diffusion combustion [24][26][27].

Due to gasoline and diesel fuel being liquid, injection causes little change in cylinder pressure. Therefore, the change in negative compression work due to fuel injection is negligible for gasoline and diesel fuel engines. However, for in-cylinder direct-injection hydrogen engines, hydrogen injection is generally carried out during the compression stroke, hydrogen will occupy a relatively large part of the cylinder volume, and the hydrogen injected has a large pressure, so it will cause an increase in compression pressure and negative compression work. However the negative compression work can be reduced by controlling the hydrogen-injection timing. Additionally, the thermal efficiency can be improved by optimizing the compression ratio and the phase of hydrogen injection. Compared with low-load uniform combustion, stratified combustion achieved by direct injection can achieve a high combustion constant volume degree, thus improving the engine efficiency. During engine operation, the combustion loss of port injection and direct injection is almost the same [28].

Compared with gasoline engines, the current port-injection and direct-injection hydrogen engines both have good effective thermal efficiency. Direct injection of hydrogen internal-combustion engines has more advantages in terms of power performance, fuel economy, and NOx emission, making it an ideal hydrogen-supply method. Compared with low-load uniform combustion, the stratified combustion can achieve a higher combustion constant volume, resulting in improved engine efficiency. The late injection strategy should be adopted to perform stratified combustion. Efficiency losses such as compression work, heat transfer to the coolant, and abnormal combustion should be reduced.

However, compared with direct-injection hydrogen engines, port-fuel-injection hydrogen engines have some disadvantages such as higher cooling loss, which results in low thermal efficiency and abnormal combustion (backfire, pre-ignition, higher burning velocity) leading to limited high-load operation. Direct injection is an effective method to overcome these disadvantages, but the combustion methods that enable both high efficiency and low NOx have not yet been thoroughly investigated.

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