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Review

Review of Combustion Performance Improvement and Nitrogen-Containing Pollutant Control in the Pure Hydrogen Internal Combustion Engine

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Abstract: Hydrogen energy is regarded as the best form to achieve the dual-carbon strategic goal of "carbon peaking and carbon neutrality". It is well-known that hydrogen energy has the characteristics of zero carbon, green, high energy, and renewable. Recently, the pure hydrogen internal combustion engine (PH-ICE) has become one of the essential directions of hydrogen energy application due to its outstanding advantages, such as no carbon emission, high efficiency, high reliability, and low pollution. So far, the PH-ICE has aroused great attention from both domestic and foreign auto companies and research institutions. This paper first introduces the latest development status of PH-ICE. Secondly, from the in-engine and out-engine technologies aspects of the PH-ICE, a comprehensive summary of its combustion performance improvement and nitrogen oxide control technology is given. Finally, the future challenges and development trends of the hydrogen ICE are discussed.

Keywords: pure hydrogen internal combustion engine (PH-ICE); combustion enhancement; nitrogen pollutants; emission control

1. Introduction

Hydrogen energy is regarded as the best form to achieve the dual-carbon strategic goal of "carbon peaking and carbon neutrality". It is well-known that hydrogen has the characteristics of zero carbon, green, high energy, and renewable [1]. Under the background of energy transformation and low-carbon and zero-carbon development of fuel, pure hydrogen internal combustion engine (PH-ICE) has become an essential direction for hydrogen energy applications due to its significant advantages [2], such as no carbon emissions, high efficiency, high reliability, and low pollution [3]. It has become a recent development hotspot for internal combustion engines, which has aroused great attention from domestic and foreign auto companies and research institutions.

As known, developing the PH-ICE has outstanding cost advantages and an industrial chain foundation since it has the long-standing experience and technology of internal combustion engines. In terms of technology, despite the fuel type of PH-ICE changes, the mixture and combustion strategy organization in-cylinder is still applicable. It can still make the best of the existing internal combustion engine industry's research, development, manufacturing, and supply chain resources. Due to the above characteristics, PH-ICE can rapidly be put into mass production, and for this point, many scholars hold a positive attitude [4,5]. Thus through continuous technology iteration and capital investment, the final cost can be close to that of the traditional internal combustion engine, which is an incomparable advantage of other new energy technologies. Therefore, the PH-ICE is an essential technical direction to promote the upgrading and transformation of various application fields of traditional internal combustion engines and assist the dual-carbon goal. Undeniably, the research and development of high-performance hydrogen internal combustion engines are crucial to energy transformation and economic development. While conducting theoretical research, many companies at home and abroad have successively announced their own hydrogen internal combustion engines. On July 1, 2022, SAIC Motor Corporation Limited successfully fired a 12.8L hydrogen fuel direct injection engine with a designed maximum horsepower of 480hp and a thermal efficiency of up to 44%. Guangxi Yuchai Machinery Group published the YCK05 hydrogen engine on December 21, 2021. This engine adopts several advanced technologies, such as high-pressure multi-point inlet injection technology, turbocharging technology, and efficient thin combustion technology, to overcome the technical problems of the hydrogen-burning engine, such as easy tempering and explosive. China FAW Group Corporation announced the successful ignition and stable operation of its self-developed direct injection in-cylinder hydrogen engine, which runs at over 500 HP and indicates a thermal power of over 55%. Cummins presented the B6.7H hydrogen internal combustion engine on September 20, 2022. The engine has a rated power of 216 kW and a peak torque of 1,200 Nm. It is a seamless replacement for diesel and is quieter than diesel.

2. In-Engine Technologies

2.1. Hydrogen Port Injection

As for the hydrogen port injection (HPI) mode, Dhyani et al. [6] conducted an experimental study on the effect of the knock phenomenon on a backfire in a spark ignition PH-ICE with the HPI method, and they found that knock created hot spots and increased the probability of backfire. Yang et al. [7] numerically investigated the effect of the HPI mode on in-cylinder mixture formation and combustion processes. The comparison results showed that the dual injection method enhances the mixture uniformity. Lee et al. [8] conducted an experimental study on the performance and emissions of an HPI spark ignition PH-ICE under lean-burn conditions. It is found that a lean mixture leads to lower combustion temperatures and longer combustion durations. Meanwhile, low exhaust temperatures and low equivalent ratios reduce nitrogen oxides (NO_x) emissions. Dhyani et al. [9] used a combination of experiments and simulations to analyze the cause of backfire and its propagation in a PH-ICE by using the HPI mode and found that the high hot spot temperature increased the probability of backfire and that the location of the hot spot had no effect on the characteristics of the backfire, but had an influence on the time of backfire onset. Şöhret et al. [10] analyzed energy and exergy in-cylinder based on experimental tests. The study showed that the indicator and effective performance parameters decreased with the decrease of compression ratio, while the exergy loss rate increased. Zhu et al. [11] used CONVERGE software to study the combustion process and nitric oxide (NO) generation rule of a PH-ICE under HPI mode. The results showed that NO decomposition mass decreases with an increasing rate of temperature decrease.

For combustion and emission characteristics. Zhu et al. [12] conducted an numerical study and found that indicated power increased with the increase of the in-cylinder pressure and temperature, and excess hydrogen promoted the reverse reaction of the thermal NO generation, which reduced NO emission effectively. Oh et al. [13] evaluated the combustion area and limitations of PH-ICE under the HPI mode. The results showed that the excess air ratio (λ) between 1.8 and 2.0 was suitable for maximum braking torque (MBT) operations. When λ reached 3, the combustion was stable, and the near-zero emission could be achieved (as shown in Figure 1). Yang et al. [14] evaluated the abnormal combustion under the HPI mode. The results showed that if the hydrogen injection angle and the hydrogen flow rate were too high or too low, which were not conducive to the formation of the gas mixture. Xin et al. [15] designed a backfire detection system for PH-ICE showing that the location and intensity of backfire occurrence was able to be determined. Marwaha et al. [16] experimentally investigated the effect of the cycle time on emissions, and the results showed that shorter cycle time or increased engine speed could lead to higher NO_x generation.

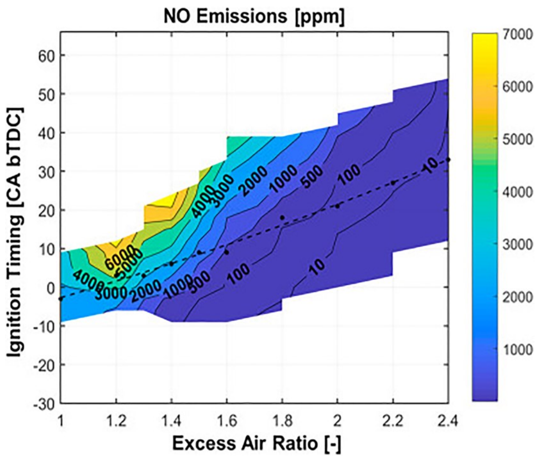

Figure 1. NO_x emissions of the PH-ICE at different excess air ratios and ignition timings using HPI. Reprinted/adapted with permission from [13].

2.2. Hydrogen Direct Injection

As for the hydrogen direct injection (HDI) mode, Li et al. [17] numerically analyzed the in-cylinder mixture formation process in a PH-ICE with HDI based on the CONVERGE software. The results showed that the injection pressure had little effect on mixture formation and combustion process. However, the secondary injection moment and injection mass fraction had a vital influence on the roll-off intensity. Ye et al. [18] numerically investigated the knock characteristics. And their results showed that extending the total injection time improved the mixture homogeneity and increased the combustion rate. Meanwhile, the knock intensity decreased first and then increased with the delay of injection timing. Bao et al. [19] evaluated the engine polytropic index and found that (1) such an index was drastically affected by the hydrogen injection process, and (2) increasing injection duration and delaying injection timing during the compression stroke could increase the average polytropic index. Li et al. [20] numerically investigated the knock characteristics where a high compression ratio was found to be effective in amplifying the impact of the equivalent ratio on the combustion knock index (KI) (as shown in Figure 2).

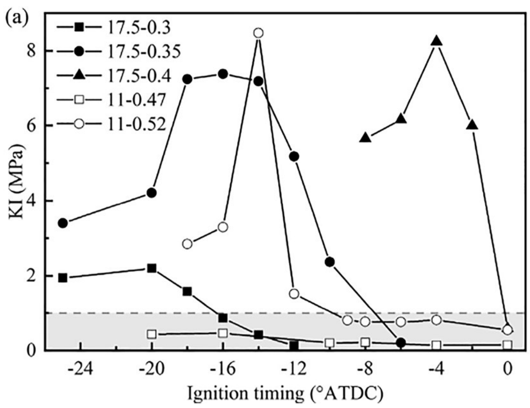

Figure 2. KI Variation of PH-ICE at different ignition timing, excess air ratios and compression ratios using HDI. Reprinted/adapted with permission from [20].

In terms of engine performance, Maio et al. [21] made a comparison under HDI and HPI modes and found that HDI allowed a more flexible organization of mixture distribution at the cost a higher wall heat loss. Addepalli et al. [22] numerically studied the influence of different structured grids on engine performance. They found that keeping the grid consistent with the main jet direction could make the results more accurate. Qu et al. [23] adopted a reduced dimensional optimization method to analyze the mixing characteristics. The analysis revealed that the mixing velocity increased with increasing mass flow rates, and the injection penetration distance increased with increasing injection pressures and injection durations. Mogi et al. [24] considered the improvement of thermal efficiency and emissions by a high compression ratio. They found that supercharge can compensate for the reduced power output due to lean-burn conditions, but a high compression ratio led to in-cylinder pressure fluctuations. Park et al. [25] considered the impact of injection strategy on output performance and engine efficiency, and the results showed that delayed injection time could improve performance and reduce emissions.

When it comes to the relationship between flame propagation and pressure waves during the knocking process, Li et al. [26] showed that the two reinforced each other and eventually developed into a knock phenomenon. Lee et al. [27] experimentally investigated the effect of different mixture formation patterns on engine efficiency and emissions. The results showed that the lean mixture could reduce heat loss and increase indicated thermal efficiency (ITE) and NO_x emission. Sementa et al. [28] experimentally compared the engine performance using pure hydrogen and methane and found that hydrogen could burn stably at low equivalent ratios and achieve near-zero emissions. Li et al. [29] evaluated the cyclic variation characteristics and found that delaying injection increased the cyclic variation coefficient. Also, the lower the engine load and λ, the higher the speed, and the more likely the influence of the start of injection (SOI) on the cyclic variation is enlargement.

2.3. Water Direct Injection

As for water direct injection (WDI) technology, Xu et al. [30] evaluated the effect of in-cylinder WDI on the combustion characteristics in a PH-ICE. It is found that WDI could reduce the combustion pressure, increase thermal efficiency, and prolong the flame development period. Xu et al. [31] experimentally investigated the effect of WDI on emission performance, and they found that early WDI timing could reduce NO_x emissions. However, delayed WDI timing worsened NO_x emissions, reduced ITE, and increased cooling losses. Dhyani et al. [32] compared the effects of WDI and exhaust gas recirculation (EGR) on abnormal combustion. The results showed that WDI could effectively reduce the probability of backfire (as shown in Figure 3) and achieve near-zero emissions without affecting engine performance.

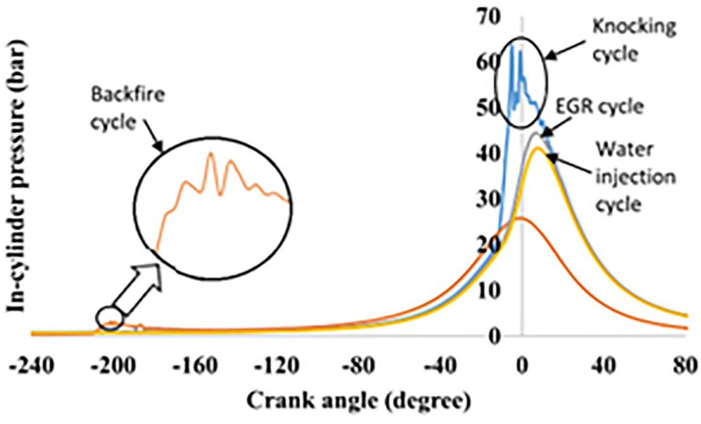

Figure 3. Combustion anomalies control of PH-ICE under WDI technique. Reprinted/adapted with permission from [32].

2.4. Compression Ignition Method

Babayev et al. [33, 34] investigated the combustion characteristics of a PH-ICE under the compression ignition (CI) mode based on a combination of simulation and experiment. They found that the free-jet mixed combustion stage was preferred over the overall in-cylinder mixing stage in the hydrogen CI mode compared with the diesel CI mode, and the brake thermal efficiency (BTE) of hydrogen was higher than or comparable to that of the diesel engine. Fernie et al. [35] used the technologies of adding peroxide (H_2O_2) and steam. And the results showed that the H_2O_2 addition led to an increase in the indicated mean effective pressure (IMEP), thermal efficiency, and a decrease in NO_x (as shown in Figure 4). When H_2O_2 and steam were under unified use, NO_x was a significant reduction, but combustion performance also reduced.

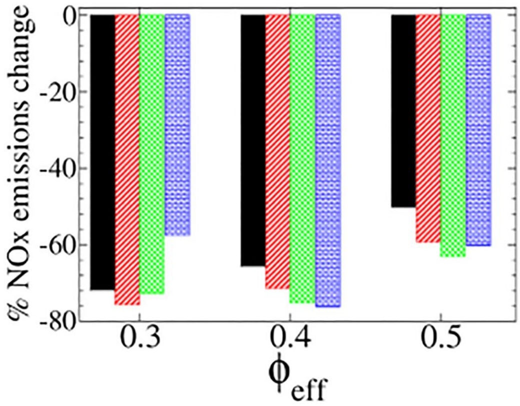

Figure 4. The variation pattern of NO_x after the addition of hydrogen peroxide to the compressed ignition PH-ICE. Reprinted/adapted with permission from [35].

In summary, the above studies involve different hydrogen injection modes, mixture ignition methods, and water direct injection technology of the PH-ICE, which mainly focuses on mixture formation, combustion efficiency and emission performance, knock characteristics and backfire, energy and exergy loss. As for HPI mode, although using HPI improves the probability of backfire, several engine external inspection devices and in-cylinder combustion control technologies can still achieve engine operation stably and meet emission standards. Compared to the HPI mode, backfiring could be avoided by the HDI engine effectively, and better performance can be obtained. In addition, under HDI mode, the engine can burn steadily at smaller equivalent ratios, and turbocharging can compensate for power loss due to lean burn. However, it can't be ignored, such as the short mixing time, abnormal combustion, and higher wall loss.

3. Out-Engine Technologies

3.1. Turbocharging

Luo et al.[36] studied the energy distribution of a turbocharged PH-ICE. They found that high speed and high load had the advantage of improving exergy efficiency. Also, a high equivalent ratio has a positive effect on improving power and the economy. Lee et al. [37] compared the performance of naturally aspirated and turbocharged engines at high loads. The comparison found that the turbocharged system stabilized combustion and increased torque output, while the high exhaust pressure increased pumping and friction losses. Wang et al. [38] analyzed the energy and exergy of a turbocharged engine. Results showed that all kinds of energies increased with engine speeds and the turbocharging increased BTE. Luo et al. [39, 40] conducted an experimental study on the performance and emissions of a spark ignition HPI turbocharged engine. The results showed that the power and combustion stability increased with increasing λ. Meanwhile, NO_x first increased and then decreased with increasing speed. When hydrogen was used simultaneously with a three-way catalyst (TWC), NOx emissions tended to be near zero.

Bao et al. [41,42] experimentally investigated the combustion and emission performance of a turbocharged hydrogen direct injection engine. The results showed that lean-burn and delayed ignition techniques could reduce thermal NO_x generation. Specifically, delayed ignition could achieve near-zero emissions at a brake mean effective pressure (BMEP) loss of only 2.5% (as shown in Figure 5). Using the turbocharging and increasing injection pressure could boost power and efficiency and achieve near-zero NO_x emissions. Bao et al. [43] tested a turbocharged engine's performance and emissions. The results showed that the peak power and maximum torque of the research prototype were increased relative to the naturally aspirated engine.

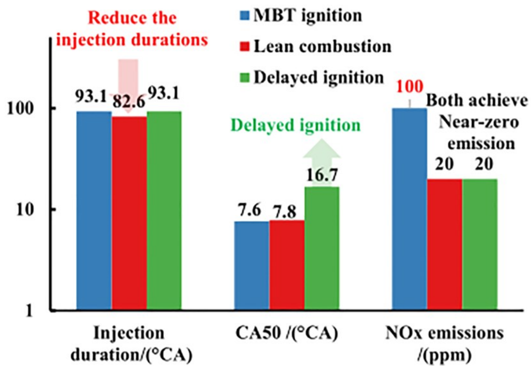

Figure 5. NO_x emission comparison between lean-burn and delayed ignition technologies of PH-ICE with turbocharging. Reprinted/adapted with permission from [41].

3.2. Exhaust Gas Recirculation

Tsujimur et al. [44] evaluated single-cylinder PH-ICE performance and emissions under HDI mode. They found that a high EGR rate could reduce NO_x emissions and abnormal combustion probability, but lead to a reduction in combustion efficiency slightly. Fischer et al. [45] evaluated the performance of a PH-ICE with external EGR. The results showed that external EGR could significantly improve the engine efficiency under the $\lambda = 1$ operating condition. Salvi et al. [46] investigated the combustion characteristics of a spark ignition engine with EGR. The analysis revealed that EGR led to a lower heat release rate (HRR) and a longer combustion duration (as shown in Figure 6). When the equivalence ratio was relatively high, EGR could reduce the knock.

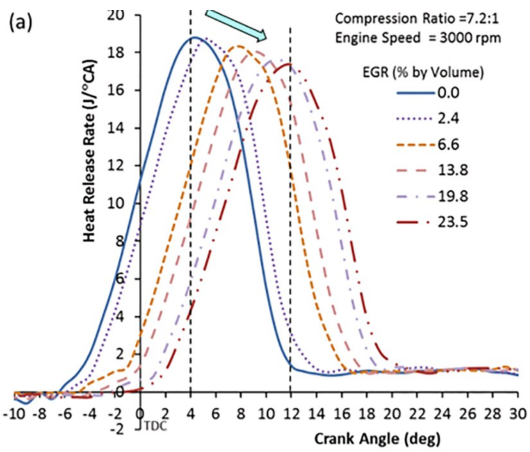

Figure 6. Exothermic rate variation pattern of PH-ICE with EGR technology. Reprinted/adapted with permission from [46].

In summary, the above studies involve the turbocharging and EGR technologies of PH-ICE and analyze the energy distribution, exergy distribution, combustion characteristics, and emission performance. Generally, the turbocharging is suitable for high load and high-speed operating conditions, and the usage of turbocharged engines can improve torque output, combustion stability, and power output, and reduce NO_x emissions. As such, the turbocharging is a feasible measure to optimize combustion and emissions performance. However, it should also be noted that a high exhaust pressure will increase energy loss, a higher EGR rate can reduce the probability of abnormal combustion, and a higher λ of EGR can reduce engine knock.

4. Multi-technology Combination

Takagi et al. [47] studied the effect of the combination of the plume ignition and combustion concept, and the supercharging on PH-ICE emissions and thermal efficiency. The results showed that it could sharply improve thermal efficiency and achieve near-zero emissions. They also found that adopting supercharging technology could compensate for the reduced power output due to lean burn. Gürbüz et al. [48] studied the effect of the external supercharger on combustion performance and efficiency under lean burn mode. Compared with the naturally aspirated, they found that the supercharger improved the IMEP, thermal efficiency, and NO_x emission, meanwhile reducing the cycle fluctuation (as shown in Figure 7). Nguyen et al. [49] experimentally investigated the effect of a supercharger on the power of PH-ICE under lean-burn and low-load conditions. Compared with turbocharging, the PH-ICE with a supercharger reduced NO_x emissions and improved output power and combustion stability. Babayev et al. [50] studied the efficiency maximization method by combining a dual compression expansion engine with high-pressure direct injection. The results showed that adding a catalytic combustor, expander adiabatic, and dehumidifying EGR to the combustion chamber could improve BTE. Oikawa et al. [51] proposed the plume ignition and combustion concept and studied the performance of PH-ICE combined with supercharging technology. The results showed that supercharging helped to improve power outputs, meanwhile optimizing the combination of SOI and λ could reduce NO_x emissions. Oh et al. [52] predicted the characteristics of residual hydrogen in engine exhaust through experiments and simulations. Their research showed that lower λ enhanced combustion and reduced residual hydrogen in the exhaust, but higher temperatures led to more NO_x emissions.

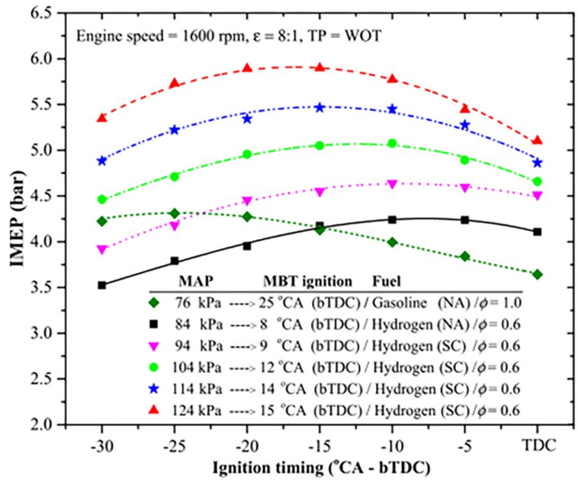

Figure 7. IMEP in a PH-ICE with ignition timing and supercharging pressure changing. Reprinted/adapted with permission from [48].

In summary, the abovementioned work mainly evaluated the multi-technology combination method to improve the combustion performance and emission characteristics of PH-ICE. The plume ignition and combustion concept can improve thermal efficiency effectively. Also, intake supercharging reduces emissions, improves combustion stability, and restores power output reduced by lean burn. In a word, the combination of multiple technologies can achieve complementary advantages and disadvantages between different technologies.

5. Conclusions and Prospects

This work reviews the effects of in-engine technologies, out-engine technologies, and combinations of multi-technology on the combustion and emission performance of PH-ICE. Firstly, HPI technology is prone to backfire problems. Meanwhile, the NOx emission is restrained by reducing combustion temperature under lean burn conditions. The HDI technology can better optimize the mixture distribution, but will bring higher wall heat loss. Optimization of the injection strategy is conducive to mixture formation and performance optimization, and the application of the WDI technology can help reduce abnormal combustion probability and NOx emission, thereby improving combustion efficiency. Comparing the combustion characteristics of the diesel engine, the BTE of PH-ICE under the compression ignition mode is higher. In addition, applying a turbocharger can improve the output torque, combustion stability, and power output, and reduce NOx emissions. Note that the turbocharger gives rise to high exhaust pressure increases energy loss despite of the fact that it is an optimized combustion and emission improvement technology. As for the EGR system, it has a positive effect on the optimization of emissions and abnormal combustion. Finally, adopting multi-technology combinations, such as the supercharging, lean burn, new ignition, and combustion mode, high-pressure direct injection, can compromize the advantages and disadvantages of the technologies so as to optimize combustion performance and pollutant emissions.

Although hydrogen energy faces some difficulties in terms of cost, storage, transportation, and safety, its prospects are very considerable, and the development potential is enormous in the future. Meanwhile, under the development trend of energy transformation, technology updates, fuel diversification, and zero carbonization, the hydrogen internal combustion engine will also exert its greatest advantages in a world filled with economic development waves.

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