

Article



Experimental Study on the Effects of Hydrogen Injection Strategy on the Combustion and Emissions of a Hydrogen/Gasoline Dual Fuel SI Engine under Lean Burn Condition

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Abstract: Hydrogen addition can improve the performance and extend the lean burn limit of gasoline engines. Different hydrogen injection strategies lead to different types of hydrogen mixture distribution (HMD), which affects the engine performance. Therefore, the present study experimentally investigated the effects of hydrogen injection strategy on the combustion and emissions of a hydrogen/gasoline dual-fuel port-injection engine under lean-burn conditions. Four different hydrogen injection strategies were explored: hydrogen direct injection (HDI), forming a stratified hydrogen mixture distribution (SHMD); hydrogen intake port injection, forming a premixed hydrogen mixture distribution (PHMD); split hydrogen direct injection (SHDI), forming a partially premixed hydrogen mixture distribution (PPHMD); and no hydrogen addition (NHMD). The results showed that 20% hydrogen addition could extend the lean burn limit from 1.5 to 2.8. With the increase in the excess air ratio, the optimum HMD changed from PPHMD to SHMD. The maximum brake thermal efficiency was obtained with an excess air ratio of 1.5 with PPHMD. The coefficient of variation (COV) with NHMD was higher than that with hydrogen addition, since the hydrogen enhanced the stability of ignition and combustion. The engine presented the lowest emissions with PHMD. There were almost no carbon monoxide (CO) and nitrogen oxides (NOx) emissions when the excess air ratio was, respectively, more than 1.4 and 2.0.

Keywords: dual-fuel engine; hydrogen injection strategy; lean burn limit; hydrogen mixture distribution; combustion; emissions

1. Introduction

With the aggravation of the energy crisis and global warming, reducing the use of fossil fuels has become a tough problem. From 2014 to 2020, China's hydrogen production rose from 16 million tons to 25 million tons. Hydrogen, as a promising renewable energy carrier and carbon-free fuel, has significant and unique physical and chemical properties [1–3].

The burning velocity of hydrogen is much higher than other fuels, such as gasoline; therefore, it is an alternative engine fuel that could effectively enhance combustion in and improve the efficiency of internal combustion engines [4–6]. As a carbon-free fuel, fueling engines with hydrogen can significantly reduce their emissions. There is no doubt that higher combustion temperatures lead to higher NOx emissions [7–10]. Nevertheless, due to the greater flammability limit of hydrogen, hydrogen-fueled engines can work under leanburn conditions, resulting in the reduction of NOx emissions. As a result, hydrogen-fueled engines can achieve lower emissions and higher efficiency [11]. However, there are also many challenges for hydrogen-fueled engines. Firstly, due to the low ignition energy of hydrogen, such engines are more prone to backfire [12]. Fortunately, supercharger systems can increase the intake pressure to limit backfire [13–15]. Secondly, hydrogen has low density and small molecules, so it is very easy for it to escape through the shell of the



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Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). storage device. Therefore, the storage of hydrogen is the key problem that must be properly solved in the development of hydrogen-fueled engines [16].

To fully utilize its advantages for combustion and avoid its disadvantages regarding storage, researchers have considered mixing hydrogen with fossil fuels to form blending fuel [17]. Numerous studies on hydrogen blending fuel have been conducted.

Since the combustion rate of diesel is relatively slow, it can be effectively improved by adding hydrogen, which has significant implications for diesel engines [18,19]. With the addition of 10% hydrogen, efficiency increased and emissions decreased [20,21]. Moreover, a reactivity controlled compression ignition (RCCI) mode has been used to increase the efficiency of diesel/hydrogen engines [22]. With hydrogen direct injection, pre-ignition in diesel engines can be attenuated, improving their limitations and emissions. Since mixing hydrogen and natural gas before injection into the cylinder can simplify the fuel injection system, there are many studies about hydrogen/natural gas engines [23–26]. The combustion rate of natural gas is worse than that of gasoline. Hydrogen has been found to help natural gas by increasing the combustion rate and decreasing the cyclic variation [27], especially under lean-burn conditions [28]. Studies have found that, with the addition of hydrogen, the combustion rate clearly increased, leading to higher efficiency and low cyclic variation [29]; combustion became more complete, leading to less emissions [30]; and the combustion temperature rose, leading to more NO_X emissions [31].

With regard to gasoline engines, hydrogen can be injected into such engines in two ways: hydrogen intake port injection (HPFI) and HDI. Ji et al. have published several studies on HPFI [32–34]. Hydrogen addition was found to improve engine efficiency, decrease emissions, extend the lean burn limit [32], speed up the cold-starting process [33] and reduce the idle speed [34]. Yu et al. have mainly focused their research on HDI [35–43]. Compared with a pure gasoline engine, HDI resulted in a quicker combustion rate and higher combustion temperature [35,36], which led to higher efficiency and fewer emissions [37]. The hydrogen in HDI is not homogeneous but stratified, which is controlled by the injection strategy [38]. With better stratification of hydrogen distribution, combustion was found to occur faster and more quickly led to lower cyclic variations and higher efficiency [39]. Furthermore, stratified hydrogen distribution is more suitable for lean-burn conditions [40–42]. Exhaust gas recirculation (EGR) systems and water injection systems can help reduce the NO_X emissions in hydrogen engines [43–45].

The hydrogen distribution in the cylinder is the main factor differentiating HPFI and HDI [45,46], and Li et al. indicated that the hydrogen mixture distribution (HMD) is the key effect in hydrogen/gasoline engines [46–50]. SHDI has been proposed to organize the HMD, as it can improve the efficiency and reduce the emissions of hydrogen/gasoline engines [49,50].

Engines show great performance under lean-burn conditions, and hydrogen addition can contribute to speeding up the combustion rate and stabilizing the ignition. The hydrogen injection strategy can significantly affect combustion through the formation of different HMDs [51]. Therefore, engine lean-burn performance can be improved using hydrogen addition and a suitable hydrogen injection strategy. However, there is little research on this topic, especially on the lean burn limits of different hydrogen injection strategies. To improve lean-burn performance and explore suitable hydrogen injection strategies for the lean burn condition, we conducted an experimental study on the effects of the hydrogen injection strategy for a hydrogen/gasoline spark ignition (SI) engine under lean-burn conditions. Four kinds of HMDs and hydrogen injection strategies were studied: HDI, forming an SHMD; hydrogen intake port injection, forming a PHMD; SHDI, forming a PPHMD; and no hydrogen addition (NHMD).

2. Materials and Methods

A schematic diagram of the test engine is shown in Figure 1. The experimental prototype was the EA888 engine from Volkswagen Automotive Company Limited, and the engine specifications are listed in Table 1.



Figure 1. Schematic diagram of the test engine.

Table 1. Engine specifications.

Engine type	Four cylinders Naturally aspirated Spark ignition	
Bore \times stroke (mm)	82.5 × 92.8	
Compression ratio	9.6	
Displaced volume (L)	2	

The measurement instruments and the experimental condition are illustrated in Tables 2 and 3, respectively. The dynamometer used was a CW160 hydraulic dynamometer. The experiment was carried out under these conditions since the hydrogen would obviously improve the engine. The excess air ratio was set at 1 to 2.8. When the excess air ratio was 2.8, the COV of the engine was more than 5%. Therefore, the excess air ratio of 2.8 was considered as the lean burn limit. The energy fraction of the hydrogen was set to 20%. Previous studies have shown that addition of a small proportion of hydrogen in an engine can significantly improve the performance, while continuing to increase the hydrogen ratio has little effect on the engine performance [41]. As split injection was used, too small a volume fraction for the hydrogen would have led to too short an injection duration. Therefore, a 20% energy fraction for the hydrogen was selected. The energy fraction of hydrogen is defined as follows:

$$\varphi = \frac{Q_{H2}}{Q_{H2} + Q_{gasoline}} \tag{1}$$

where φ is the energy fraction of the hydrogen, Q_{H2} is the energy of the hydrogen and $Q_{gasoline}$ is the energy of the gasoline.

Table 2. Information on measurement instruments.

Item	Error	Measurement Instrument		
Gasoline consumption	$\leq \pm 0.01 \text{ g/s}$	Ono Sokki DF-2420		
Crank angle (CA) position	≤±0.01 °CA	Ono Sokki DS 9028		
Cylinder pressure	$\leq \pm 0.3$ bar	Ono Sokki DS 9028		
Speed	$\leq \pm 1 \text{ rpm}$	CW160		
Brake power	$\leq \pm 0.4\%$	CW160		
Hydrogen consumption	$\leq \pm 0.2\%$	DMF-1-1AB		
Emissions	$\leq \pm 0.1\%$	AVL DICOM 4000		
Excess air ratio	$\leq \pm 0.15$	LSU4.2 oxygen sensor		

HMD	NHMD	SHMD	PHMD	PPHMD
Speed (r/min)	1200			
Throttle opening (%)	10			
Excess air ratio	1 to 2.8			
Ignition timing (°CA BTDC)	Best			
Hydrogen fraction	0%		20%	
Direct injection pressure (MPa)	/		5	
Second injection timing (°CA BTDC)	/	Best	/	Best
First injection proportion	/	/	/	Best
First injection timing (°CA BTDC)	/	/	300	300

Table 3. Experimental conditions.

To demonstrate the differences between injection strategies clearly, the injection parameters and ignition timing were set to the best values on the basis of efficiency.

Figures 2 and 3 show the best injection parameters for the SHMD and the PPHMD. With the increase in the excess air ratio, the best hydrogen injection timing for the SHMD and the best second hydrogen injection timing for the PPHMD were delayed. Moreover, the fuel in the engine became thinner and harder to ignite. Delayed hydrogen injection made more hydrogen concentrate around the spark plug, and the engine ignition performance was improved. Therefore, the engine worked more steadily and efficiently. The best second hydrogen injection timing for the PPHMD was later than that for the SHMD. Due to the two injections with the PPHMD, the amount of hydrogen in the second hydrogen injection is less than that of the SHMD, so a greater hydrogen around the spark plug was the key to ensure the engine ignition performance. Since ignition became more difficult with the increase in the excess air ratio, the best first hydrogen injection proportion for the PPHMD decreased from 33% to 25%.



Figure 2. The best injection timings under lean-burn conditions.



Figure 3. The best first hydrogen injection proportions under lean-burn conditions.

3. Results and Discussions

Figure 4 shows the effects of the HMD on the brake thermal efficiency. With the NHMD, the lean burn limit of the engine was the excess air ratio of 1.5. Since the lean burn limit of hydrogen was much greater with hydrogen addition, the lean-burn performance was greatly improved and the excess air ratio could reach 2.8.



Figure 4. Effects of the HMD on the brake thermal efficiency.

Since the oxygen content increased with the increase in the excess air ratio, combustion was more complete and the power capacity of the engine was also enhanced. Moreover, the combustion speed of the engine was reduced and the ignition performance deteriorated. Therefore, with the increase in the excess air ratio, the brake thermal efficiency of the engine first increased and then decreased. With the NHMD, the maximum brake thermal efficiency appeared at the excess air ratio of 1.2. The lean-burn performance was significantly improved by adding hydrogen. With the PPHMD, when the excess air ratio was 1.5, the maximum brake thermal efficiency appeared at 26.86%. The efficiencies of the SHMD and the PPHMD were relatively higher. This may have been due to the fact that the stratified hydrogen made the engine more efficient. The stratified hydrogen formed a hydrogen concentration zone around the engine spark plug, making the engine ignition

process faster and more stable. Therefore, the efficiency of the stratified hydrogen was higher. With the increase in the excess air ratio, the best HMD changed from the PPHMD to the SHMD, and the engine ignition performance became the key for the engine efficiency. The hydrogen in the SHMD was injected into the engine cylinder at one time and the hydrogen concentration was the highest.

Figure 5 shows the effects of the HMD on the cylinder pressure. With the increase in the excess air ratio, since the quantity of fuel in the engine decreased, the maximal cylinder pressure (Pmax) and the combustion speed decreased continuously. As the best ignition timing was adopted, the level of the maximal cylinder pressure was kept within a certain range. With the increase in the excess air ratio, the combustion of the engine became slower, the ignition timing advanced and the combustion duration increased. The engine cylinder pressure with the NHMD was higher, as the best ignition timing with the NHMD was earlier than that with hydrogen addition.



Figure 5. Effects of the HMD on the cylinder pressure: (**A**) NHMD, (**B**) SHMD, (**C**) PHMD, (**D**) PPHMD.

Figures 6 and 7 indicate the effects of the HMD on the Pmax and its corresponding position. With the increase in the excess air ratio, the total amount of fuel in the engine decreased, resulting in a continuous decrease in the Pmax of the engine. However, by adjusting the ignition time, the position of the Pmax could be kept within a certain range. The maximal cylinder pressure under the excess air ratio of 2.8 decreased by 46.19% on average compared to that with the excess air ratio of 1.0. The increased excess air ratio resulted in the best HMD (in terms of the Pmax) changing from the PPHMD to the SHMD. This result further verified that the engine ignition performance was the key to lean combustion efficiency.



Figure 6. Effects of the HMD on the Pmax.



Figure 7. Effects of the HMD on the position of the Pmax.

Figure 8 shows the effects of the HMD on the coefficient of variation. The stability of the ignition decreased with the increase in the excess air ratio, which reduced the combustion speed and increased the COV of the engine. It was noted that the COV with the NHMD was higher than that with hydrogen addition. In this study, hydrogen addition increased the ignition and combustion stability of the engine significantly, so that the lean burn limit extended from an excess air ratio of 1.5 to 2.8.



Figure 8. Effects of the HMD on the COV.

Figure 9 displays the effects of the HMD on the CO emissions. When the excess air ratio increased, the reduction in the fuel and the increase in the oxygen concentration in the engine contributed to a sharp decrease in CO emissions. It can be seen from the figure that, when the excess air ratio was greater than 1.4, the CO emissions in the engine were almost zero. Moreover, the different hydrogen injection modes showed notable effects on the engine CO emissions under the equivalent ratio conditions, while the effects decreased rapidly with the increase in the excess air ratio. Since the gasoline was reduced by 20%, the CO emissions with hydrogen addition were 24.72% lower than with the NHMD.



Figure 9. Effects of the HMD on the CO emissions.

Figure 10 shows the effects of the HMD on the hydrocarbon (HC) emissions. It was noted that the HC emissions showed a trend of decreasing first and then increasing. The oxygen concentration increased with the increase in the excess air ratio, resulting in lower HC emissions. However, with the further increase in the excess air ratio, especially when it was close to the lean burn limit, the HC emissions of the engine increased sharply because of the extreme deterioration of combustion and misfire. With the SHMD, the lowest HC emissions appeared at the excess air ratio of 1.6. In terms of different HMDs, the HC emissions with the NHMD were the greatest and those with the PHMD were the lowest. The engine combustion was more complete with hydrogen addition because of the decrease in the wall quenching distance, which meant that the HC emissions significantly. The HC emissions with the PHMD were, on average, 4.01% lower than with the PHMD, 14.07% lower than with the SHMD and 51.96% lower than with the NHMD.



Figure 10. Effects of the HMD on the HC emissions.

Figure 11 illustrates the effects of the HMD on the NOx emissions. The NOx emissions increased first and then decreased with the increase in the excess air ratio. The conditions for the generation of NOx emissions were high temperature and high oxygen concentration. When the excess air ratio increased, the temperature in the engine was reduced, while the oxygen concentration in the engine kept increasing; therefore, the NOx emissions first increased. With the further increase in the excess air ratio, the combustion deteriorated and the temperature gradually decreased, resulting in a sharp drop in the NOx emissions. For the NHMD, the highest NOx emissions occurred with the excess air ratio of 1.1, and they increased by 10.60% when the excess air ratio was 1.0 and by 446.09% when the excess air ratio was 1.5. With an excess air ratio greater than 2.0, there were almost no NOx emissions because of the low temperature. The NOx emissions were the lowest with the NHMD. The stratified hydrogen in the SHMD enhanced the ignition and combustion, thus resulting in the highest NOx emissions. The NOx emissions with the NHMD were 42.22% lower than with the PHMD, 45.08% lower than with the PPHMD and 47.21% lower than with the SHMD.



Figure 11. Effects of the HMD on the NOx emissions.

4. Conclusions

The effects of hydrogen injection strategies for a gasoline/hydrogen engine with various excess air ratios were investigated. The main conclusions of this research are summarized as follows:

- 1. The lean-burn performance could be improved with hydrogen addition. In this study, the lean burn limit with the NHMD was the excess air ratio of 1.5, while with 20% hydrogen addition, it was the excess air ratio of 2.8;
- 2. With the increase in the excess air ratio, the brake thermal efficiency of the engine first increased and then decreased. Moreover, hydrogen addition improved the brake thermal efficiency. With the NHMD, the maximum brake thermal efficiency (23.83%) appeared at the excess air ratio of 1.2, while with the PPHMD, the maximum brake thermal efficiency increased to 26.86% at the excess air ratio of 1.5;
- 3. With the increase in the excess air ratio, the best HMD changed from the PPHMD to the SHMD. Since the engine ignition became the key factor under lean-burn conditions, the hydrogen concentration around the spark plug was the highest with the SHMD;
- 4. The COV of the engine increased with the increase in the excess air ratio, since the engine ignition became unstable and the engine combustion was slower under lean-burn conditions. The COV with the NHMD was higher than that with hydrogen addition, which was because hydrogen addition improved the ignition and combustion stability;
- 5. The HC emissions first decreased and then increased with the increase in the excess air ratio because the increase in oxygen concentration led to the deterioration of

combustion. The HC emissions were the highest with the NHMD and the lowest with the PHMD. The hydrogen concentration affected the HC emissions significantly. The HC emissions with the PHMD were, on average, 4.01% lower than with the PPHMD, 14.07% lower than with the SHMD and 51.96% lower than with the NHMD;

6. The NOx emissions first increased and then decreased with the increase in the excess air ratio since the engine temperature was reduced and the oxygen concentration increased. When the excess air ratio was greater than 2.0, there were almost no NOx emissions. The NOx emissions were the lowest with the NHMD and the highest with the SHMD. The NOx emissions with the NHMD were, on average, 42.22% lower than with the PHMD, 45.08% lower than with the PPHMD and 47.21% lower than that with SHMD.

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Abbreviations

Nomenclature

φ	energy fraction of hydrogen
Q _{H2}	the energy of hydrogen (J)
Q _{gasoline}	the energy of gasoline (J)
Abbreviation	
SI	Spark Ignition
HMD	Hydrogen Mixture Distribution
SHMD	Stratified Hydrogen Mixture Distribution
PHMD	Premixed Hydrogen Mixture Distribution
PPHMD	Partially Premixed Hydrogen Mixture Distribution
NHMD	No Hydrogen Mixture Distribution
СО	Carbon Monoxide
HC	Hydrocarbon
NOx	Nitrogen Oxides
RCCI	Reactivity Controlled Compression Ignition
COV	Coefficient of Variation
HDI	Hydrogen Direct Injection
SHDI	Split Hydrogen Direct Injection
EGR	Exhaust Gas Recirculation
CA	Crank Angle
BTDC	before Top Dead Center

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