Study on Emission Characteristics of Hydrogen Direct-Injection Gasoline Engine

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Abstract. Experiments have been carried out on a hydrogen direct-injection and gasoline port-injection engine at the conditions of locally rich hydrogen and lean-burn mode in order to study the effect of hydrogen fraction and air-fuel ratio on the engine’s emissions. The experiments results demonstrated that when the excess-air ratio was increased from 1 to 1.8, NOx and CO emissions were at least decreased by 91% and 95% respectively and HC emission was increased by 56%. Almost 23% reduction was observed in HC emission when hydrogen fraction changed from 3.9% to 10.5%, whereas the NOx emission has almost been tripled and CO emission is found to be less affected with hydrogen fraction.

1. Introduction
Two most favourable methods to injection of hydrogen into the combustion are direct injection (DI) and port fuel injection (PFI) [1]. The literature on PFI is more comprehensive than that of directly injected engines with gaseous fuels. However, the way of PFI also exists some shortcomings such as low volumetric efficiency, pre-ignition and backfiring. In order to eliminate these risks of irregular combustion, DI is considered a more suitable fuel injection process than PFI. The hydrogen is directly injected into the combustion chamber after intake valve closing (IVC) which avoids the air displacement effect in the intake manifold [2]. It also provides great flexibility in optimizing an engine’s mixture formation by varying injection timing, duration, and pressure as well as injector location, combustion chamber geometry and nozzle configuration [3]. Furthermore, hydrogen direct injection can achieve high compression ratio at lean burn state, increase engine efficiency, reduce emissions and also avoid engine knock by producing a hydrogen enrichment area in spark plug and taking full advantage of hydrogen characteristics such as wide lean limit, low ignition energy which efficiently improve the characters of ignition and combustion of lean-burn model.

Air-fuel ratio has a major influence on the performance of hydrogen fueled engine and hydrogen-gasoline engine. M.Rahman [4] studied the effects of air-fuel ratio on performance of direct hydrogen fueled engine. It could be seen from the obtained results that air-fuel ratio was greatly influenced on the brake mean effective pressure (BMEP), brake efficiency (BE), brake specific fuel consumption (BSFC) as well as the maximum cylinder temperature. It could be seen that BMEP, BE and maximum cylinder temperature were decreased with the increase of air-fuel ratio, however, the brake specific fuel consumption was increased. In addition, M. Akif Ceviz, et al. [5] investigated engine performance, exhaust emissions, and cyclic variations in a lean-burn SI engine fueled by gasoline-hydrogen blends. Results show that at air-fuel ratio of 1.2, CO and HC emissions were reduced by about 89% and 20%, respectively, compared to stoichiometric conditions. For this air-fuel ratio, the thermal efficiency increased by about 20%, and the specific fuel consumption decreased by about 20% in comparison to
stoichiometric conditions. However, there are few literatures about the hydrogen direct-injection gasoline engine until now. In this paper, the authors investigated the effect of hydrogen fraction, excess-air ratio and ignition timing on the engine’s NOX, HC and CO emissions.

2. Experimental device and procedure

2.1 Experimental device
The main parameters of the engine are listed as follows, the type of engine is 4 cylinders and 16 valves, the bore and stroke are 82.5mm and 84.1mm, the compression ratio is 9.6, the displacement is 1.8L, the rated power is 118 kW (5000-6200 r/min), and the maximum torque is 250 N·m (1500-4200 r/min). The engine was reformed to a hydrogen in-cylinder direct injection engine from a gasoline port injection engine. Fuel injection timing, ignition timing and pulse width of the engine were controlled by a self-developed electronic controlled unit. Figure 1 shows the layout of the engine experiment bench.

![Figure 1. Layout of the engine experiment bench.](image)

A series of sensors, including exhaust air pressure sensor, intake air temperature, coolant temperature sensor, exhaust air temperature sensor, intake air pressure sensor were mounted to the engine in order to collect its working state parameters. The concentration of exhaust CO, CO2, O2, NOX and HC were measured by AVL DiCom 4000 light vehicle exhaust analyzer. Its measurement range and resolution are shown in table 1.

| Test item | Measurement range | Resolution |
|-----------|-------------------|------------|
| CO        | 0~10%Vol.         | 0.01%Vol.  |
| CO2       | 0~20%Vol.         | 0.1%Vol.   |
| HC        | 0~20000ppm Vol.   | 1ppm       |
| NOX       | 0~5000ppm Vol.    | 1ppm       |
| O2        | 0~25%Vol.         | 0.01%Vol.  |

2.2 Experimental procedure
In order to simulate the typical city-driving condition of a heavy traffic, the engine speed of the experiment was fixed at 1500 rpm. The injection pulse width and pressure of hydrogen were altered in order to regulate the volume fraction of hydrogen entering into the cylinders, which included the percentage of 3.9%, 5.3%, 7.2%, 8.9% and 10.5%. The injection pulse width of fuel was altered in order to regulate the excess-air ratio under a hydrogen fraction. By the program in the self-developed electronic controlled unit, the engine could work under its ignition advance angle.
3. Result and discussion

3.1 Effects of hydrogen fraction and excess-air ratio on NOx, HC and CO emissions

As shown in figure 2, NOx, HC and CO emissions change obviously with the excess-air ratio under the conditions of MBT and different hydrogen fractions. As illustrated in figure 2, NOx emissions reached peak when the excess-air ratio is 1.2. This is because the rising of oxygen concentration in cylinders promotes the fuel burn sufficiently, at the same time hydrogen addition boosts burning rate, gets the combustion temperature higher, and promotes the NOx generate. When lambda is greater than 1.2, the heat release rate reduces and the temperature in cylinder declines. The temperature is a critical factor that affects the emissions of NOx, so NOx emissions decrease gradually with the decreasing of the temperature in cylinder. When the excess-air ratio is 1.5 and the percent of hydrogen is less than 7.2%, NOx will be under 1000 ppm. This is because the increase of temperature in cylinder caused by little hydrogen fraction can’t offset the loss of temperature caused by the reduced excess-air ratio, which makes NOx emissions descend rapidly. While when the hydrogen fraction is greater than 7.2% or equal to 7.2%, hydrogen addition promotes the fuel burning rapidly, keeps temperature at a high level, and remains NOx emissions under 2000 ppm. When the excess-air ratio is greater than 1.8, it is difficult to keep an efficient and rapid burning. Moreover, the thermal efficiency and heat release rate drop dramatically, meanwhile temperature in cylinder keeps at a low level. It restrains NOX generating, which makes NOx emissions level reduce to 500 ppm.

As illustration of figure 3, HC emissions descend to minimize when the excess-air ratio is 1.2, and then go along with the increasing of the excess-air ratio, HC emissions rising slowly. This is attributed that when the excess-air ratio increases from 1 to 1.2, oxygen concentration in cylinder increases and the fuel burns efficiently, so the emissions of HC descend. When the excess-air ratio continues to increase, combustion deterioration, the phenomenon of after-burning and incomplete combustion aggravate because of the narrow lean combustion boundary of gasoline. In addition, with the increasing of the excess-air ratio, engine exhaust temperature descends, the later stage oxidizing of HC decreases, which makes the HC emissions continue to increase. However, when the percent of hydrogen is greater than 5.2%, the emissions of HC can keep a low level when the excess-air ratio is below 1.8. This is because hydrogen addition can improve lean burn limit of mixture, hamper the increasing of HC emissions that caused by misfire; In addition, the quenching distance of hydrogen is short, after hydrogen addition, the flame is more close to cylinder wall. Furthermore, burning can go deep into the clearance between the piston and cylinder wall, which efficiently reduces CO emissions that caused by cranny effect, at the same time the diffusion ability of hydrogen is greater than gasoline, which makes mixture in cylinder more uniform. It is advantageous to burn the mixture and descend HC emissions efficiently. When the excess ratio is greater than 1.8, the mixture is too lean, which
influences the spread of flame, preventing the fuel burning completely. The probability of misfire cycle is bigger and bigger in cylinder and the emissions of HC rise significantly.

Figure 3. Effect of the excess-air ratio on HC emissions.

CO emission with different excess-air ratio is shown in figure 4. When the excess-air ratio increase from 1.0 to 1.2, as the oxygen concentration is increased to promote fuel combustion, CO emissions decrease rapidly. It is observed in this process, CO emissions decrease with the increasing of hydrogen fractions. This is because hydrogen addition is beneficial for full combustion and cylinder temperature improving, thus it suppresses the generation of CO. When lambda is greater than 1.2, the in-cylinder oxygen concentration increases, promoting CO oxidation to CO$_2$, in addition lean limit is expanded after hydrogen addition, so that CO emissions of hydrogen gasoline engine remain at a low level with high excess-air ratio. When lambda is greater than 1.8, local extinction happens, consequently the generation of CO accelerates due to the decreasing of in-cylinder temperature. Furthermore, the exhaust temperature reduces rapidly with the increasing of the excess-air ratio. It is not good for CO to be oxidized to CO$_2$, so the CO emissions increase slightly.

Figure 4. Effect of the excess-air ratio on CO emissions.

3.2 Effects of ignition timing and excess-air ratio on NOx, HC and CO emissions

Figure 5 to figure 7 shows the change of NOx, HC and CO emissions with the ignition timings under different excess-air ratio when hydrogen fraction is 3.9%. The trends of their emissions at any ignition timings are the same with the trends at the best ignition timing as shown in figure 2 to figure 4. It is also observed that the emissions gaps under different excess-air ratio increase when the ignition advance angle is greater than 10°CA. This shows that the effects of air-fuel ratio on emissions are more obvious at bigger ignition advance angle.
4. Conclusions
(1) With the increase of the air-fuel ratio, NO\textsubscript{X} emissions present a trend, which firstly increase and then decrease and reach maximum value at lambda = 1.2, HC and CO emissions decrease to minimum value at lambda = 1.2.
The increase in air-fuel ratio results that HC emissions increase slightly and CO emissions remain at a low level. Lean combustion can effectively reduce emission of CO and NOX.

Increase in hydrogen fraction leads to the decrease of HC and CO emissions, but slight increase in NOX emissions. The variation law of emissions with the excess-air ratio is little affected by ignition timing.

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