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Effects of hydrogen direct injection strategy on characteristics of lean-burn hydrogen–gasoline engines

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HIGHLIGHTS

- Hydrogen direct injection offers a flexible way on coupling of hydrogen and gasoline.
- Hydrogen-gasoline blends can increase power output by 10% and thermal efficiency by 4.5%.
- The effect of injection pressure on power output is further that of injection timing.
- Hydrogen addition improves engine stability on lean burn conditions.
- The combined effect of lean burn and hydrogen addition can reduce NOx emission by 55%.

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ABSTRACT

To study the effects of hydrogen direct injection strategies on the characteristics of combustion and emissions of hydrogen–gasoline engines, an experimental engine platform was built with gasoline intake injection and hydrogen direct injection. The effects of hydrogen injection pressure and injection timing at a minimum advance for the best torque on the characteristics of engine combustion and emissions were studied at a constant engine speed, air–fuel ratio, and hydrogen fraction. The test results showed that when the heat that was released in the cylinder was constant, a 10% hydrogen fraction had a significant influence on the engine's performance, combustion, and emissions. Hydrogen direct injection greatly improved the combustion stability of lean-burn mixtures of the engine, and significantly improved the mean effective pressure and thermal efficiency. Hydrogen injection at optimum ignition timing would significantly shorten the flame-development period and rapid combustion duration. The heat release was more concentrated, which increased the cylinder pressure. With an excess air ratio of 1.5, the addition of hydrogen significantly reduced CO emissions, but HC emissions increased slightly. A lean burn could contribute to the reduction of NO*x* emissions, whereas the addition of hydrogen would increase it.

1. Introduction

Replacing fossil fuels with clean and renewable energy is an effective method to liberate the automotive industry from design pressures imposed by energy shortages and environmental pollution [1,2]. Hydrogen can provide green and clean energy because of its special physical and chemical properties, and it is used to optimize the performance of conventional combustion engines [3,4].

Compared with common fossil fuels such as gasoline, diesel, and natural gas, hydrogen has wider combustion limits, such as a faster flame-propagation speed, a lower ignition energy, and a faster diffusion rate [5–7]. However, the heat value of mixture of hydrogen and air is very low because of hydrogen's low density. Therefore, its power density is lower than that of other fuels [8]. In addition, hydrogen is more difficult to store, which limits the total fuel storage of a pure hydrogen engine [9]. However,

Abbreviations: CO, carbonic oxide; HC, hydrocarbon; NO*x*, nitrogen oxidation; H2ICE, hydrogen-fueled internal combustion engine; GDI, gasoline direct injection; RON, research octane number; ECU, electronic control unit; CA, crank angle; BTDC, before top dead center; CA50, 50% heat release of the total hydrogen–gasoline fuel mixture; COV, coefficient of variation; φH_2, the fraction of hydrogen addition; *q*Gas, the heat produced by gasoline; qH_2, the heat produced by gasoline and hydrogen.

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hydrogen is more suitable for use in a blended fuel in engines. By adding hydrogen to conventional fuels, the engines can achieve a higher efficiency and improve combustion quality and fuel economy while reducing emissions [10,11]. Owing to increasingly mature on-vehicle hydrogen-production technology, adoption of hydrogen-addition techniques in automobiles is promising [12,13]. Compared with pure hydrogen engines, hydrogen-addition engines use less hydrogen, and on-vehicle hydrogen-production technology could provide and store sufficient hydrogen [14–16], thus reducing dependence on infrastructure such as hydrogen-replenishment stations. In addition, hydrogen-addition engines require only a small modification to conventional engines, which reduces research and manufacturing costs significantly.

There have been many studies on adding hydrogen into a spark ignition engine. Ji et al. [17,18] studied the lean-burn performance of a hydrogen-blended gasoline engine under wide-open-throttle conditions. The results showed that after adding hydrogen, an increased brake mean effective pressure was found only at lean-burn conditions, and toxic emissions, including HC, CO, and particulates, were reduced. Pantile et al. [19] showed that applying the hydrogen direct injection method in the engine cylinder at the beginning of the compression stroke after the intake valve closes could avoid reducing the specific power. Sopena et al. [9] optimized the conversion of a commercial spark ignition engine into an engine that runs on hydrogen. Their study showed that the thermal efficiency of a H_2 internal combustion engine (ICE) was greater than that of a gasoline-fueled engine, except for the fact that the H_2 ICE worked at very lean conditions ($\lambda = 2.5$) and high speeds (above 4000 rpm). The studies by Zhao et al. [20] indicated a more stable and faster combustion as more hydrogen was blended, and a substantial reduction in particulate emissions was found at low-load conditions.

Hydrogen can be mixed with gasoline by intake-port or in-cylinder injection. Compared with intake-port injection, in-cylinder injection does not take up the volume of the intake charge and can avoid inlet backfire effectively [10,21,22]. Because hydrogen has a lower ignition energy and faster flame speed, after a certain amount of hydrogen is injected into a cylinder, it forms a mixture that could easily build a steady flame kernel. In this way, it could ignite a thinner mixture and improve combustion stability [23]. Moreover, the amount of hydrogen, the injection timing, and the size of the injection zone of in-cylinder injection can be controlled accurately, which, according to chamber shape and air flow, will form different hydrogen–gasoline-blend distribution states on demand to ignite lean mixtures in cylinders [24–27]. Hydrogen that is blended by direct injection can improve the lean-burn stability of gasoline-fueled engines significantly, extend the lean-burn limits, and improve the traditional gasoline-fueled-engine thermal efficiency. If lean-burn technology is applied to gasoline engines, for example, a greater compression ratio can be used, which results in a leaner mixture, a greater adiabatic index, and a larger throttle opening, and increases the power performance and fuel economy.

During lean burn, however, the formation of a flame kernel is more difficult to achieve, the flame speed decreases and the combustion duration is prolonged [28], which increases the amount of unburned and incomplete combustion of the fuel. In general, it is believed that an excess air ratio in a gasoline engine should be 1.5 for lean-burn conditions to be achieved. The gasoline engine easily misfires when the actual excess air ratio is greater than 1.5, which decreases the power and fuel economy of the engine and increases the HC, CO, and particulate emissions. Therefore, a flame kernel that can burn steadily and stable flame propagation are needed to improve the combustion process of the gasoline engine. Mixing a small amount of hydrogen with direct injection can make up for the shortcomings mentioned above, and improve the thermal efficiency of the gasoline engine. In addition, the lean-burn condition of gasoline engine can greatly suppress the increase in temperature caused by adding hydrogen, thereby alleviating a substantial increase in NOx emissions. The combustion and emission characteristics of lean-burn gasoline engines with hydrogen direct injection were studied by the authors, and the lean-burn performance, fuel economy, emission, and cold-start performance were all greatly improved [11,29–31].

The study of hydrogen blended with fossil fuels to improve the combustion quality of internal-combustion engines is of great significance [32–34], but more research has focused on the way in which hydrogen is mixed with air or other gaseous fuels. Because of the special physical and chemical properties of hydrogen, its injection into the cylinder with a specific injection strategy will provide for the formation of hydrogen enrichment around the spark plug, and a total stratified mixture concentration in the cylinder. This result is more conducive to the burn of a lean mixture that is ignited by hydrogen, and improves the lean combustion stability. The least amount of hydrogen is used to achieve optimized combustion and emissions.

Therefore, it is necessary to investigate the influence of hydrogen direct injection on dual-fuel engines. Based on our previous work [29–31], some macroscopic parameters such as excess air ratio and hydrogen fraction were shown to have a significant positive effect on the combustion and emission characteristics of an engine with hydrogen direct injection. However, some microscopic parameters, such as hydrogen injection pressure and timing, have not been studied yet. Therefore, the effects of hydrogen injection pressure and injection timing at an optimum ignition timing on the combustion and emission characteristics of an engine were studied by using an experimental platform with gasoline intake injection and hydrogen direct injection.

2. Experimental apparatus and method

2.1. Experimental apparatus

The experimental engine used in this study was a gasoline engine with gasoline port injection and hydrogen direct injection, which was modified from a gasoline direct injection (GDI) engine. The main specifications of the original engine are listed in Table 1. A gasoline supply system is installed at the intake manifold of the engine for injecting and pre-mixing gasoline. The hydrogen pipeline is connected with the fuel-supply line of the original engine to supply hydrogen into the cylinder. A set of electronic control unit (ECU) systems was used to control the injection pulse and timing of the injector, which were located in the intake port and cylinder, respectively. In addition, the throttle opening is also controlled by the ECU. The schematic diagram of the experimental setup is shown in Fig. 1.

Table 1 shows the experimental systems. An AVL-GU13Z-24 pressure transducer was mounted in the glow plug adapter of the engine head to obtain cylinder pressure. Crank angle signals were collected with a Kistler 2614B crank-angle encoder. The com-

Table 1
Technical specifications of the tested engine.

Engine type	Four cylinder, water cooled
Displacement	1.798 L
Bore	82.5 mm
Stroke	84.2 mm
Compression ratio	9.6:1
Rate power/speed	118 kW/(5000–6200 rpm)
Rate torque/speed	250 Nm/(1500–4200 rpm)
Number of valves per cylinder	4