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Full Length Article

Effect of hydrogen proportion on lean burn performance of a dual fuel SI engine using hydrogen direct-injection

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HIGHLIGHTS

- Hydrogen addition improved the burning rate of mixture and flame velocity.
- Hydrogen acts as a flame kernel while setting fire on mixture.
- Lean-burn performance gets improved due to extended flammability after hydrogen added.
- Carbonic emission reduced with additional of hydrogen.
- Direct injection combined with tumble flow enhanced the effect of hydrogen addition.

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ABSTRACT

Hydrogen is a fuel that has low ignition energy, wide inflammability limit and superb combustion rate, using hydrogen-enriched gasoline mixture in SI engine is a favorable way to improve the performance of burning process, particularly in lean-burn condition. Hydrogen direct injection allows forming stratified mixture with back fire prevention and independent with intake air content. An experimental investigation was performed to analyze the stratified lean-burn characteristics of a hydrogen-enhanced gasoline engine with hydrogen direct injection. Five different hydrogen additional fractions (3.9%, 5.3%, 7.2%, 8.9%, and 10.5%) were used under four different excess air ratios (1, 1.2, 1.5, and 1.8) with 1500 rpm of engine speed. Hydrogen injection timing was optimized to form a stratified mixture. The result obtained demonstrated that flame developing duration and combustion duration were reduced after hydrogen added, the engine performed higher in-cylinder pressure and heat release rate with the increase of hydrogen proportion as well as effective thermal efficiency. Due to the improvement on combustion rate, the MBT was retarded close to the TDC. Cyclical variation was reduced and lean-burn limit was extended. In addition, HC and CO emissions were reduced while NOx emission increased with addition of hydrogen. The PM emission remains a low level.

1. Introduction

Due to the large base and rapid increase of vehicle population over the world, the huge demand for fossil fuel and anxious for air pollution caused by vehicle exhaust turned into the most remarkable issues at present. Research and application on alternative fuel for internal combustion engines are drawing more attention [1].

Hydrogen has been treated as a privileged alternative fuel due to its properties and unlimited sources [2]. As a clean and active fuel, hydrogen possesses high burning rate, wide inflammability limit, and easy to be ignited [3]. Considering the shortage of energy density and difficulties in storage, pure hydrogen is not suitable to be used in engines [4,5]. However, blending small amount of hydrogen in gasoline engines turned out to be a favorable way to enhance the operation efficiency [6–10].

Blending hydrogen in gasoline engines can improves the burning rate of mixture and reduces the misfire rate [11], the mixture burns more sufficiently, thus more energy can be released in a shorter period, causing a higher combustion temperature which signifies the enhancement on the conversion efficiency from energy to work in Otto cycle [12]. What's more, the lean-burn operation mode can be introduced which improves the thermal

Abbreviations: SI, spark-ignited; MBT, minimum spark timing for best torque; TDC, top dead center; BTDC, before top dead center; CO, carbon monoxide; HC, hydrocarbon; NOx, nitrogen oxide; PM, particulate matter; COV, coefficient of indicated mean effective pressure variation; PFI, port fuel injection; GC, gravity center of heat release rate; IMEP, indicated mean effective pressure.

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efficiency and reduces the burning rate simultaneously due to the leaner mixture. The lean-burn mode allows the engine operating at wide open throttle (WOT) condition which is very effective on saving pumping loss [13]. The addition of hydrogen offsets the defect of lean-burn mode and improves the thermal efficiency of the engine to a further step [14]. Many researches have been conducted on the hydrogen-blended gasoline engine. Shivaprasad et al. [15] found that the engine brake torque and brake thermal efficiency get improved with addition of hydrogen till 20% by volume. For 25% by volume, brake power dropped due to combustion deteriorated as the hydrogen occupied too much of air content in the intake pipe. Ji et al. [16–19] learnt that the BMEP gets enhanced and the MBT is retarded after hydrogen blended under lean conditions by experiments. Besides, the flame velocity was increased and the degree of flame wrinkling was enhanced by calculation. Ceviz et al. [20] concluded that the advantage of lean-burn mode can be fully used by blending some hydrogen with nothing unfavorable to driving stability. Tahtouh et al. [21] recorded high speed images which showed that the acceleration on flame propagation velocity by adding hydrogen was more effective in initial stage of combustion process than following stages. Yüksel et al. [22] found that the supplementation of hydrogen in gasoline engines reduced heat dissipation to coolant and unaccounted losses by 36% and 30% respectively. However, all of the researches above were concentrated on port fuel injection (PFI) engine.

Compared with port injection, hydrogen direct injection has unique advantages in improving effective torque output while solving troubles such as knocking, backfiring and pre-ignition [23]. According to Wimmer, direct injection of hydrogen offers an improvement of 42% in volumetric efficiency [24]. With hydrogen direct injection, the distribution of hydrogen can be organized on condition that the injection timing matches up with the injection area and tumble flow, which was considered essential to achieve better combustion performance [25]. A proper concentration of hydrogen surround the ignition area enhanced the thermal efficiency while cutting down the heat flow transferred to cylinder wall [26]. Hamada et al. [27] found that 130 CA BTDC of injection timing was considered to form a stratified mixture while 150 CA BTDC was insufficient which gone against with combustion improvement.

The engine performed different advantages with different combination of gasoline and hydrogen injection location [28]. Based on the variability of injection timing and area, hydrogen direct injection can be employed in hydrogen-blended gasoline engine to improve the engine performance to a further step. Pana et al. [29] concluded that this solution of hydrogen fueling system has proven its real functionality and offers flexibility in hydrogen flow control. But only a few researches were conducted on this due to its difficulties on controlling and complexities on cooperating with many parameters. In this paper, gasoline is port injected in the intake pipe while hydrogen is direct injected into cylinders at a certain timing, thus under the guide of air flow, a stratified gasoline-air-hydrogen mixture could formed with gasoline-air mixture full filled the cylinder volume homogeneously while a small amount of hydrogen concentrated on the top of combustion chamber [30]. Hydrogen is easy to be ignited and diffuse, which plays an important role in forming flame kernel of high quality and inducing the ambient gasoline-air mixture catch on fire. This combustion strategy ensures the successful rate of ignition with the help of hydrogen and generates enough power output depends on the homogeneous gasoline-air mixture in the same stroke [38]. Shi et al. [28,31,32] found that about 10% of thermal efficiency was improved while about 35% of specific fuel consumption was saved when 30% of hydrogen was direct injected compared to gasoline operation at $\lambda = 1$. Pantile et al. [33] injected the hydrogen after the intake valve close, learnt that the effective power and brake thermal efficiency increased as the hydrogen percent increased due to its better combustion properties, and combustion duration decreased due to the greater combustion speed of hydrogen comparative to gasoline.

Since the hydrogen direct injected gasoline engine is a new research field, earlier studies have attempt to reveal the discipline and obtained some staged objectives. However, they just revealed some partial aspects of the engine. As an engine system, a thoroughly research is needed. This paper employed broader test conditions, analyzed the relationship between power performance and exhaust emissions based on combustion performance of hydrogen-gasoline mixture in cylinders, devotes to exhibit the latest and most comprehensive research results on hydrogen direct injected gasoline engines.

2. Experimental set-up and procedure

2.1. Experimental set-up

The test engine was based on a 1.8 L four-cylinder engine of which parameters were summarized in Table 1. For the requirements of this experiment, port fuel injectors on the intake pipe and direct injectors for hydrogen were installed. Gasoline was supplied through the oil rail up to 0.6 MPa of pressure, and hydrogen was feed through the high pressure hydrogen rail up to 10 MPa to the direct injectors. The hydrogen was stored in special hydrogen bottles.

The engine was connected to CW160 dynamometer to remain a constant speed. We used FST-OPEN measuring system to meter torque output of engine (measuring accuracy: $\leqslant$0.1%). Fuel consumption was obtained by Ono Sokki DF-2420 flow meter (measuring accuracy: $\leqslant$0.01 g/s). AVL ZF42 pressure transducer (measuring accuracy: 16 pC/bar) was used to acquire in-cylinder pressure and calculate other combustion parameter by Ono Sokki DS9100 combustion analyzer. The flow rate of intake air was measured by BOSCH flowmeter (measuring range: 0–400 kg/h). The λ was measured by LSU4.2 oxygen sensor installed on exhaust pipe. Hydrogen flow rate was calculated based on the measurement result of lambda meter, gasoline mass flowmeter and intake air mass flowmeter, due to the difficulties in measuring ultra-low flow rate of hydrogen. The exhaust component was measured by AVL DICOM-4000 exhaust analyzer and PM emissions were detected by TSI EESP 3090 engine exhaust particle size spectrometer.

2.2. Experimental procedure

This experiment is mainly focused on the effect of the hydrogen additional fraction on the lean-burn combustion performance under low and medium load conditions, hence the engine speed is fixed at 1500 rpm, which could represent the typical operating conditions in the urban and suburb roadway.

Gasoline was injected into the intake pipe through the PFI injector to form a homogeneous gasoline-air mixture in the cylinder which provides a favorable initial environment for the combustion process. Then hydrogen was injected directly into the cylinder at some point to generate a hydrogen-enriched zone around the spark plug which was easily to be ignited and the flame could spread out

Table 1
Engine specification.

Item	Characteristics
Engine type	Four cylinders; split injection; naturally aspirated; spark-ignited
Bore * stroke	82.5 mm * 84.2 mm
Compression ratio	9.6
Displaced volume	1.8 L