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Comparison study and synthetic evaluation of combined injection in a spark ignition engine with hydrogen-blended at lean burn condition

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ABSTRACT

This study contributes to synthetic improvement and evaluation of energy efficiency and cleaner production by using combined injection in a gasoline-hydrogen blended engine bench. According to the previous published literature, few researches deal with combined injection technology, especial hydrogen combined injection. The equivalence ratio was kept at 0.77 and the energy input into the engine was constant. Some main conclusions were got that as for the PFI + GDI mode and the GDI mode, higher injection pressure could lead to longer spray penetration distance and better atomization, but excessive direct injection pressure may cause spray wall impingement and deteriorate the engine emissions performance. As for the PFI + HDI mode (90% gasoline and 10% hydrogen, energy ratio), a small amount hydrogen could improve the engine torque effectively and rise 5.34% than the PFI mode in average value and further reduce CO by 13.98%, HC emissions by 30.03%, but increase NOx emissions by 179.31% than the PFI mode. After hydrogen addition, increase of the direct injection pressure could suppress the forming of the accumulation mode particles. In the range of accumulation mode, the particle number (PN) concentration of the PFI + HDI mode reduced 26.1% than the PFI mode, reduced 35.66% than the PFI + GDI mode and reduced 12.28% than the GDI mode. Meanwhile, a comprehensive evaluation of different injection modes were obtained.

1. Introduction

Aiming at meeting the requirement of energy saving and emissions reduction, new technology and new energy source have been a hot area in the engine researchers' focus [1]. Based on port fuel injection (PFI), which is also known as manifold injection, traditional gasoline engines have the advantage of low particulate matter (PM) emissions [2]. While gasoline direct injection (GDI) is widely regarded as a practical technology to reduce fuel consumption [3], reduce unburned hydrocarbon (HC) emissions [4], and improve transient response [5]. So the combination of PFI and GDI seems to complement each other, thereby getting environmental-friendly fuel injection strategies to obtain efficient energy utilization and clean production. This combined injection technology has been applied in some vehicle type. Mou et al. [6] performed a series of experiments which were carried out on a gasoline engine equipped with combined injection technology and the results showed that the fuel injector in the cylinder head could be used to enrich the mixture near the spark plug, which is contributed to form a better stratified mixture. Huang et al. [7] investigated the effect of ethanol heating on the EDI + GPI (ethanol direct injection plus gasoline port injection) engine performance. The results showed that CO and HC were significantly reduced and NO was slightly increased by EDI heating.

Hydrogen is one of the new secondary energy sources expected as a salvation of conventional energy crises and the development of new secondary energy sources [8]. Nowadays hydrocarbon reforming is the main method to produce hydrogen and steam methane reforming (SMR) is the most common and developed method for large-scale hydrogen production [9]. Compared to conventional hydrocarbon fuel, hydrogen has the advantages of low ignition energy, high flame propagation speed, high diffusion rate and wide ignition limit [10]. Therefore, hydrogen addition can effectively increase combustion stability and improve the engine

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Nomenclature

PFI	port fuel injection
DI	direct injection
GDI	gasoline direct injection
PFI + GDI	port fuel injection plus gasoline direct injection
PFI + HDI	port fuel injection plus hydrogen direct injection
SMR	steam methane reforming
RON	research octane number
MBTT	maximum brake torque timing
MBT	maximum brake torque
HC	hydrocarbon
CO	carbon monoxide
NOx	nitrogen oxides
EGR	exhaust gas recirculation
PM	particulate matter
PN	particle number
ECU	electronic control unit
CA	degree crankshaft angle
TDC	top dead center
BTDC	before top dead center
SI	spark ignition
DP	diameter of particle

performance. More importantly, hydrogen is a carbon-free energy, which will not produce pollutants such as carbon monoxide (CO), unburned hydrocarbon (HC), dust particles and so on [11]. Good ignition stability of hydrogen can also reduce emissions caused by cyclic variations [12]. Based on the above-mentioned advantages, hydrogen especially as a fuel extender, has been constantly studied in the field of internal combustion engines.

Wang et al. [13] noted that after mixing 6% hydrogen, the idle speed of the pure gasoline engine decreased from 800 RPM to 600 RPM. Meanwhile, with the increase of the hydrogen volume fraction, the combustion duration was shortened, the HC, CO and NOx emissions were reduced and the cyclic variation was reduced. Reyes et al. [14] found the combustion rate of natural gas engine increased and the combustion stability improved with the increase of hydrogen mixing ratio. Verma et al. [15] performed an experimental study in an ignition butanol engine. In Verma's study, with hydrogen addition, the engine thermal efficiency was improved and the HC and CO emissions went down. Mohammed et al. [16] developed one-dimensional model with gasoline–hydrogen and methane–hydrogen blends and analyzed the engine performance in terms of the hydrogen mass fraction, engine speed and equivalence ratio.

A lot of literature considered the hydrogen added in the engine with PFI, but ignored the backfire caused by the preignition when ignited air–fuel mixture explodes backward into the inlet valve system, which is very hazardous to the researchers and equipment [17]. Whereas hydrogen direct injection (HDI) can effectively avoid backfire [18]. More researchers conducted experiments based on HDI. Zhao et al. [19] got some conclusions that the combustion stability was improved greatly as more hydrogen was blended at all load conditions in a spark ignition (DISI) engine with hydrogen and gasoline direct injection. With the stoichiometric mixture at low load, the total PM number and total PM mass reduced up to 90% with 5% of stoichiometric hydrogen blended and reduced the total number up to 97%, the total mass by up to 95% with 10% of stoichiometric hydrogen blended. Di et al. [20] concluded that for hydrogen/methane blends combustion, the mixture was more homogeneous and have higher efficacy on the propagation flame speed.

From the above literature review, it is easy to find that most of the published literature focus on hydrogen utilization in the field of internal-combustion engine but seldom involve combined injection technology. So there is lack of investigation on the combined injection coupled with hydrogen utilization. Previous studies of our group focus on some aspects such as cycle-by-cycle variations [21], particle emissions [22], cold start characteristics [23] and hydrogen proportion [24] with a hydrogen-blended gasoline engine. A deeper understanding of hydrogen utilization in engines has formed. In this work, a new energy utilization strategy coupled with hydrogen and combined injection technology was proposed. This proposal will further improve energy efficiency and find the route of cleaner production. Eventually, combustion and emissions performance of a spark ignition engine with this new coupled application was investigated. Meanwhile a comprehensive evaluation of different injection modes was made as well.

2. Experimental setup and experimental method

2.1. Experimental setup

The test object is a 4 cylinder ignition gasoline engine with combined injection technology. Through the electronic control unit (ECU), the port fuel injection (PFI) mode, port fuel injection plus gasoline direct injection (PFI + GDI) mode, port fuel injection plus hydrogen direction injection (PFI + HDI) mode can be achieved. Fig. 1 illustrates the positions of the two injectors and the spark plug. The technical parameters of the original gasoline engine are shown in Table 1. The detailed test bench and test instrument system are shown in Figs. 2 and 3.

The parameters of test instruments are shown in Table 2. The engine torque and speed were controlled by a CW160 eddy current

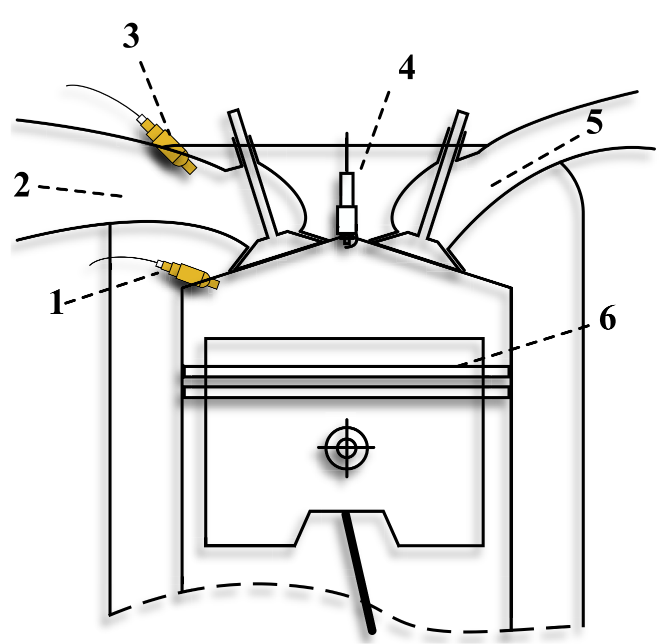

Fig. 1. Combustion chamber layout sketch. 1. Cylinder direct injector; 2. Intake port; 3. Port injector; 4. Spark plug; 5. Exhaust port; 6. Piston.