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# Lean burn performance of a hydrogen-blended gasoline engine at the wide open throttle condition

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## HIGHLIGHTS

- The performance of a $H_2$-blended gasoline engine at the WOT condition was studied.
- The engine became run stable after the $H_2$ addition.
- $H_2$ addition resulted in the raised thermal efficiency for the gasoline engine.
- Both number and mass of particulate emissions were reduced by the $H_2$ addition.
- $H_2$ addition reduced the engine knocking tendency at full loads.

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## ABSTRACT

The performance of a hydrogen-blended gasoline engine at lean and the wide open throttle conditions was investigated. A hydrogen port-injection system was adopted to introduce the hydrogen into each cylinder. The engine was operated at 1400 rpm and two hydrogen blending levels of 0% and 3%. The excess air ratio was raised from 1.00 to about 1.45 for a given hydrogen addition fraction. The test results demonstrated that the hydrogen blending contributed to the raised thermal efficiency and shortened flame development and propagation durations. An increased brake mean effective pressure was found after the hydrogen addition only at lean conditions. For both stoichiometric and lean conditions, the hydrogen blending was beneficial for reducing the engine cyclic variation. This provides a possibility to run a hydrogen-blended gasoline engine with the fully opened throttle position and control the engine torque only by adjusting the excess air ratio. Toxic emissions including HC, CO and particulate were reduced after the hydrogen blending.



## 1. Introduction

The daily increased energy crisis and demand on environmental protection have stimulated studies on clean and renewable alternative fuels for vehicles. In recent years, many efforts have been put on developing the alternative fuel for internal combustion engines, such as ethanol–gasoline engines [1–3], methanol engines [4,5], and dimethyl ether-blended engines [6]. Among all fuel candidates, hydrogen is generally believed to be a promising alternative fuel for the internal combustion engines. Different from fossil fuels, hydrogen can be produced through kinds of ways [7–10], such as water electrolysis, fuel reforming and biological hydrogen production. This makes the hydrogen-based power system become important to the nation energy safety. There are three typical ways for applying hydrogen on vehicles [11–14], which are fuel cells, pure hydrogen engines and hydrogen-blended engines. Generally, the fuel cell-powered vehicles produce few harmful emissions during the driving time. However, the high price and limited life span of fuel cells are generally barriers for its commercialization at present. Besides, the limited hydrogen infrastructure distribution also makes the refilling of fuel cell vehicles difficult in many countries. Furthermore, spark ignition engines are still used worldwide. This makes improving the thermal efficiency and reducing toxic emissions of internal combustion engines more important for ensuring the nation energy safety and environmental protection. The combustion of pure hydrogen engines is cleaner than the traditional gasoline and diesel engines, but the pure hydrogen engines always suffer the high NOx emissions and dropped power output [15]. Besides, abnormal combustion phenomenon, such as pre-ignition and knock, is prone to be appeared in pure hydrogen engines [16,17]. Compared with fuel cells and pure hydrogen engines, the

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hydrogen-blended engine is also capable of gaining less toxic emissions and better fuel economy [18–20]. Generally, converting a conventional gasoline engine to be fueled with hydrogen–gasoline blends requires adding a hydrogen injection system to the engine, and the hydrogen could be stored in the hydrogen cylinders or provided by the onboard hydrogen producer, which is usually introduced to the hydrogen injectors through a stainless steel made hydrogen supply system. Besides, to accomplish the hydrogen injection, the program of engine electronic control unit has to be improved accordingly. Although it needs time and work to accomplish these work, as it does not need to redesign the engine or massive improvements in the powertrain system, realizing the hydrogen blending to a conventional gasoline engine is feasible and not a very tough work. Thus, the hydrogen blending is a promising approach to better engine performance in the near future.

Basically, improving the combustion process of fossil fuel is important on enhancing the engine overall performance. The effect of hydrogen addition on the combustion properties of fossil fuels has been done by Huang et al. [21,22]. It was found that the hydrogen blending availed accelerating the flame propagation for natural gas-air mixtures. Besides, a combustion simulation model was built and calibrated. Based on this model, they observed that the hydrogen blending to methane contributed to promoting the formation of OH, O, and H in the flame. These could help shorten the combustion duration of fuel–air mixtures and therefore reducing the engine cooling and exhaust losses. Furthermore, they also found that the flame shape and position became stable after the hydrogen enrichment. This is generally helpful for easing the engine cyclic variation. Except for the investigations on basic combustion properties of hydrogen-blended fossil fuels, there are also some investigations which have shown the effect of hydrogen enrichment on engine performance. Regarding the daily increased urgency for energy saving, it was demonstrated that the addition of hydrogen was capable of enhancing thermal efficiency of the natural gas, LPG and gasoline engines [23–28]. According to Lata et al. [24–27], a 17% improvement in thermal efficiency was found for the LPG engine after the hydrogen addition. Reasons for the improved engine thermal efficiency were generally believed to the shortened combustion duration and enhanced combustion completeness which contributed to the dropped cooling and exhaust losses. Furthermore, because of the short quenching distance of hydrogen, the addition of hydrogen was also proved to be helpful for reducing the engine HC and CO emissions [29,30]. Navarro et al. [31] also found that because the hydrogen was a carbonless fuel, the addition of hydrogen also availed reducing carbon dioxide emission from the engine. However, because of the high flame temperature of hydrogen, NOx emissions from the hydrogen-enriched fossil fuel engines were generally higher than those from conventional engines [29,30]. Fortunately, because of the wide flammability of hydrogen enabled the hydrogen-enriched engine to run stably at much leaner conditions [32,33], NOx emissions from the hydrogen-enriched engines could be controlled by adopting lean combustion strategy. Investigations done by Diéguez et al. [28] found that NOx emissions were decreased to near zero when the hydrogen-natural gas blends-fueled engine was run at very lean conditions. To further improve the performance of hydrogen-enriched engines, Ji et al. [34] proposed a control strategy which changes the hydrogen-to-gasoline ratio according to the engine working conditions for the hydrogen-enriched gasoline engine. By adopting this controlling strategy, the engine fuel economy was improved and the toxic emissions during the legislated new European driving cycles (NEDC) were obviously reduced for the hydrogen-blended gasoline engine-powered vehicle.

Operating an engine at the wide open throttle (WOT) condition is very effective for reducing the engine pumping loss [35], especially for the naturally-aspirated engines. Moreover, the enhanced charge motion at the WOT condition also leads to the dropped residual gas fraction which contributes to the improved engine combustion. According to previous study [36], because of the increased charge heating capacity, the application of exhaust gas recirculation (EGR) was helpful for inhibit the knocking of spark ignition engines. Xie et al. [37] tried to run a methanol engine at the WOT condition and control the engine load through adjusting the spark timing and the ratio of EGR. They confirmed that the engine brake mean effective pressure can be changed between 0.36 and 0.96 MPa at the un-throttled condition by properly controlling the spark timing and EGR ratio. However, according to investigations carried out by Fontana and Galloni [35], the engine volumetric efficiency tended to be decreased by increasing EGR ratio at the WOT condition. This would lead to higher residual gas fractions which may deteriorate in-cylinder combustion. Generally, the challenge for running an SI engine at the WOT condition is knocking. Due to the elevated temperature in combustion chamber, the end gas tends to be auto-ignited. Particularly, for the hydrogen engines, the high flame temperature of hydrogen may make the pure hydrogen engines are much easier to encounter knock at high loads [38].

However, although running an SI engine at the WOT condition is beneficial for enhancing the combustion and reducing the pumping loss, there are limited papers examining the operating characteristics of an engine fueled with hydrogen–gasoline mixtures under the WOT condition. As running an engine at the un-throttled condition is effective on promoting the engine fuel economy and reducing the emissions, this paper experimentally investigated the operating characteristics of an engine fueled with hydrogen–gasoline mixtures under the WOT condition. As the application of lean combustion contributes to the reduced cylinder temperature [39] which may be helpful for overcoming knocking in spark ignition engines, the tests are mainly conducted under lean conditions.

## 2. Experimental set-up and methodology

### 2.1. Experimental set-up

The test engine is a naturally-aspirated Beijing Hyundai manufactured gasoline engine with a displacement volume of 1.6 L, a rated torque of 143.28 N m at 4500 rpm and a rated power of 82.32 kW at 6000 rpm. Before this experiment, a hydrogen port-injection system was added so that the engine can be fuelled with the hydrogen–gasoline blends. The hydrogen injection system contains a hydrogen rail and four hydrogen injectors placed on the runners of each cylinder. Besides, in order to govern the hydrogen and gasoline injection durations and spark timing, a hybrid electronic control unit (HECU) was applied. Through changing programs in the HECU, the hydrogen blending level, engine spark timing, and excess air ratio of the fuel–air mixtures could be adjusted in real time.

A GW160 eddy current dynamometer was applied to govern the engine speed by putting loads on engines (measurement uncertainty: ±0.28 N m and ±1 rpm). Two thermal flow meters typed 20N060 and D07-19BM were applied to record the hydrogen and air flow rates, respectively (measurement uncertainty: <±0.1 and ±0.02 L/min for air and hydrogen, respectively). The mass flow rate of gasoline was detected by a FC2210 fuel mass flow meter (measurement uncertainty: <±0.33 g/min). The engine in-cylinder pressure was recorded through a Kistler 6117BFD17 piezoelectric pressure sensor (measurement uncertainty: <±0.3 bar). The crankshaft position was recorded by a Kistler 2613B optical encoder (measurement deviation: <±0.01 °CA, crank angle resolution: 0.2 °CA). Then, to conduct the insight combustion analysis, the engine crank angle signals and cylinder pressure were sent to a