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DEVELOPMENT AND PERFORMANCE OF A PLUG-IN HYBRID HYDROGEN VEHICLE

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ABSTRACT

To reduce the fuel consumption and toxic emissions, this paper developed a plug-in hybrid hydrogen vehicle (PHHV). The PHHV is powered by a hybrid hydrogen-gasoline engine (HHGE) which is fueled by the pure hydrogen at the cold start to minimize HC and CO. For normal working conditions, the HHGE is fueled with hydrogen and gasoline simultaneously to gain higher thermal efficiency. Furthermore, the PHHV has adopted the idle elimination and hydrogen restart strategy to cancel the idling condition. The hydrogen consumed by the HHGE is produced by an onboard water electrolysis hydrogen generator placed in trunk of the PHHV. The hydrogen generator could gain electricity from charging pile of the electric vehicle to realize the plug-in hydrogen production. The performance of PHHV is also tested according to the New European Driving Cycle. The test results showed that, compared with the original engine fueled with the pure gasoline, HC, CO and NOx emissions from the PHHV were respectively reduced by 57.8%, 52.1% and 10.2% within the driving cycle. Moreover, PHHV also acquired a 12.2% reduction in the total fuel consumption.

Keywords: Hydrogen, Plug-in H2 generation, Gasoline, Spark-ignition engine, Emissions, Vehicle.

NONMENCLATURE

Abbreviations

PHHV	Plug-in hybrid hydrogen vehicle
HHGE	Hybrid hydrogen gasoline engine
NEDC	New European driving cycle
ICE	Internal combustion engine
EV	Electric vehicle

1. INTRODUCTION

Hydrogen is thought to be one of the best fuel candidates for spark-ignition engines [1,2]. Compared with traditional hydrocarbon fuels, hydrogen has a wider flammability limit, a lower ignition energy, and higher adiabatic flame speed and temperature. These properties of hydrogen enable the hydrogen engine to gain higher thermal efficiency than conventional fuel engines. However, the wide commercialization of hydrogen engines tends to be limited by its high NOx emissions, abnormal combustion behaviors of backfire and pre-ignition, and the short driving mileage resulted from limited hydrogen infrastructures distribution.

Compared with the pure hydrogen engines, the hydrogen-enriched engines which are fueled with hydrogen and other hydrocarbon fuels could also gain better combustion and emissions characteristics than the traditional engines. Park et al. [3,4] investigated the performance of hydrogen-blended natural gas engines. His study showed that the engine lean burn limit was extended after the hydrogen addition. For a heavy-duty natural gas engine, the engine thermal efficiency was averagely increased by 0.74% with hydrogen enrichment. Chintala et al. [5,6] found that the addition of hydrogen could improve thermal efficiency of compression ignition engines. Although NOx emissions were increased after the hydrogen blending, HC and CO emissions were decreased obviously for the hydrogen-enriched engines. Ji and Wang et al. [7-9] conducted detailed investigations on performance of hydrogen-enriched gasoline engine under the cold start, idle, part load and full load conditions. They found that the engine would run with high efficiency and low emissions for all tested conditions if the hydrogen-to-gasoline fraction were properly controlled. Yu et al. [10,11] investigated the effect of directly injected hydrogen on performance of a gasoline engine. Their results showed that the engine lean burn limit could be further extended through adjusting the hydrogen injection timing and distribution.

Different from the pure hydrogen engines, for the hydrogen-enriched engines, the hydrogen is used as an additive. Therefore, the hydrogen could be produced by an onboard hydrogen generator. This makes the driving mileage of hydrogen-enriched engine-powered vehicles is not limited by the difficulties in hydrogen refilling. Almeida et al. [12] ran a vehicle driven by the hydrogen-enriched ethanol engines. In the test, the hydrogen was provided by an onboard water electrolyzer. The test results indicated that the onboard hydrogen producer could operate stably and provide enough hydrogen for the hydrogen-enriched ethanol engines.

Ji and Wang et al. [7] also tested the performance of a vehicle powered by the HHGE based on NEDC procedure. They found that HC and CO could be reduced obviously through adopting the coordinative control of fuel and operating conditions strategy. However, since the electrolysis of water consume electricity from generator, although the engine combustion was improved by hydrogen addition, less improvement was found for the fuel economy. This is because the onboard hydrogen production results in energy losses in water electrolysis and electricity generation by IC engines. At the same time, the electric voltage onboard the vehicle is generally around 12V which is relatively low for water electrolysis. For low voltages, the electric current would be increased to meet the power requirement. This could results in higher heat loss during hydrogen production and bring potential dangerous of fire.

To further improve the performance of hybrid hydrogen engine powered vehicles, this paper proposed a plug-in hydrogen generating strategy which enabled the water electrolyzer to gain electricity from charging pile of electric vehicles. Then, the performance of PHHV was tested on the chassis dynamometer though NEDC testing procedure.

2. DEVELOPMENT OF PHHV

2.1 Construction of PHHV

The development of PHHV is based on a D50 car produced by BAIC Motor. The prototype engine used in the vehicle is a four cylinder, port fuel injected, spark-ignition gasoline engine with a displacement of 1.5 L. Fig. 1 gives the construction of PHHV. Compared with the conventional gasoline engine powered vehicle, a hydrogen production and storage system, a hydrogen injection and control system, and an electric power supply system are added for the PHHV. The hydrogen is produced by a water electrolyzer placed on trunk. The water electrolyzer has a weight of 35 kg and a power of 500 W, which could produce the hydrogen at a rate of 1.8 L/min. A hydrogen tank placed in the trunk and an oxygen tank placed on bottom of chassis outside the trunk are connected to the hydrogen generator. Four hydrogen injectors are added to runners of each cylinder, the hydrogen is kept at 3 bar through pressure regulator before entering the hydrogen rail and injectors. One oxygen injector is placed before the throttle to inject oxygen at 3 bar.

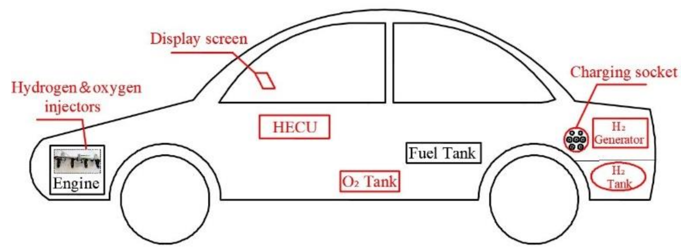

Fig. 1 The schematics of PHHV

An AC/DC adapter was developed for realizing the plug-in hydrogen production. The AC/DC adapter has a power of 1 kW which could convert 220 V AC input to 36 V DC output. When the hydrogen pressure in storage system is low, or when it is convenient to produce the hydrogen through nearby EV charging pile, drivers could stop the car and insert the AC/DC plug to EV charging pile. Then, the AC/DC adapter could communicate and gain electricity from the EV charging pile, and supply the hydrogen generator with 36 V DC power through cables to enable the hydrogen electrolyzer to produce hydrogen. In China, the development of EV has pushed EV charging pile distribution. It is generally convenient and cheap to get electricity from it.

Furthermore, a hybrid electronic control unit (HECU) was developed for PHHV, which was adopted to control the injection pulses of hydrogen and gasoline, as well as controlling engine spark timing and run/stop of the hydrogen generator.

2.2 Control strategy of PHHV

The detailed PHHV control strategies are shown in Fig. 2. According to previous studies [13], the engine cold start process could account for 70% to 90% total HC and CO emissions within the driving cycle. Thus, the PHHV is started with the pure hydrogen to minimize HC and CO emissions. Considering the traffic jam in cities, the PHHV also adopted the idle elimination strategy. When the HECU detects that the vehicle is run at the idle, it would automatically stop the engine. When the clutch or throttle pedals is slightly pressed, the HECU would restart the engine with the pure hydrogen for 1 s. Then, the gasoline fraction is gradually increased, and after 2 s the engine is run with either hydrogen–gasoline mixtures or the pure gasoline depending on the engine load. This strategy could totally eliminate the fuel consumption and emissions at the idle. Meanwhile, restarting the HHGE in PHHV with the pure hydrogen also ensures a quick and clean starting process.

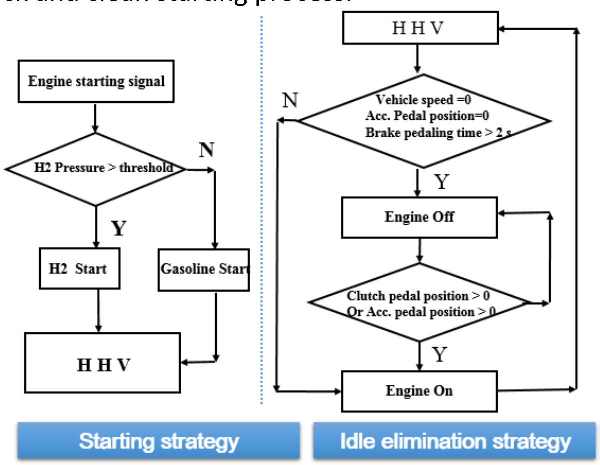

Fig. 2(a). Starting and idle elimination strategies

Since the addition of hydrogen could potentially decrease the engine power output at high loads considering its low volumetric energy density, it is reasonable to adjust the hydrogen addition fraction according to the engine operating condition to realize the coordinative control of fuel and engine conditions [7]. In the PHHV, the hydrogen blending is enabled only when the engine load is lower than 75%. Besides, according to results from our previous investigations, the hydrogen blending fraction is increased with the decrease of engine load. The oxygen injection is enabled only when the driver requires a sharp acceleration or the vehicle runs at the high altitudes. When the driver sharply steps on the accelerator pedal, the HECU could inject the oxygen for 2 s to quickly increase the oxygen fraction in the cylinder. This could enable the engine to burn more fuel with higher oxygen fractions, and quickly improve the engine working capability.

3. VEHICLE TEST OF PHHV

3.1 Experimental setup

The schematic diagram of the experimental system is shown in Fig. 3. All instruments are calibrated and functioned according to NEDC testing procedure [14].

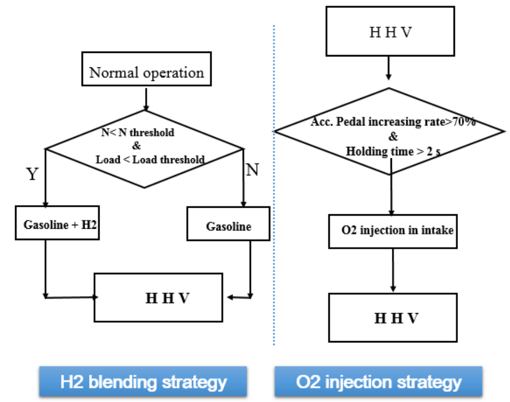

Fig. 2(b) H2/O2 blending strategies

The vehicle is loaded by an Ono Sokki PECD-9400 chassis dynamometer. Horiba MEXA-7200H emissions analyzer is applied. The emissions analyzer measures the instantaneous emissions through a direct sampling line from the constant volume sampling system (CVS), which is also used to analyze the vehicle overall emissions performance during the NEDC test by measuring gas concentration in the CVS bag. The measurement uncertainties are less than ±1% of the measured values.

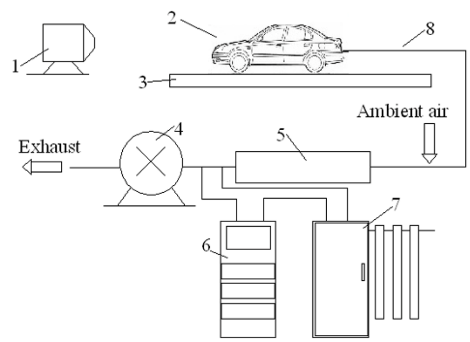

Fig. 3 The schematics of the experimental system

1. Fan 2. Test vehicle 3. Chassis dynamometer 4. Blower 5. Dilution tunnel 6. Emissions analyzer 7. Constant volume sampling system with bag 8. Sampling line

3.2 Testing procedure

The vehicle was soaked in the lab for 12 hours at an ambient temperature of 20.6 ^{o}C before each individual test. The experiment was conducted according to the NEDC testing standard. Two fueling strategies were tested. The first was the original gasoline engine powered vehicle test. In this test, all parameters are controlled by the original vehicle. In the 2nd test, PHHV was fueled with the strategy introduced in Section 2.2.

4. TESTING RESULTS AND DISCUSSIONS

Fig. 4 shows variations of HC, CO and NOx emissions with time within the NEDC testing. The vehicle speed is also given as a reference. It could be seen from Fig. 4a that the original gasoline vehicle exhaust many HC at the cold start. The PHHV exhaust much less HC emissions during the starting, since the combustion of hydrogen produces no carbon emissions. Meanwhile, the addition of H2 also helps improve combustion. Fig. 4b indicates that the PHHV produces much lower CO than the original vehicle. This is because PHHV operates with the mixture that has higher H/C ratio that avails reducing carbon related emissions. Besides, the PHHV eliminate the CO peak for each acceleration from idle, since the PHHV adopted the idle elimination and pure hydrogen restart strategy. By adopting idle elimination and hydrogen rich combustion, NOx from PHHV are also kept at low levels. According to results, HC, CO, NOx and fuel consumption of PHHV are reduced by 57.8%, 52.1%, 10.2% and 12.2%, compared with the original vehicle.

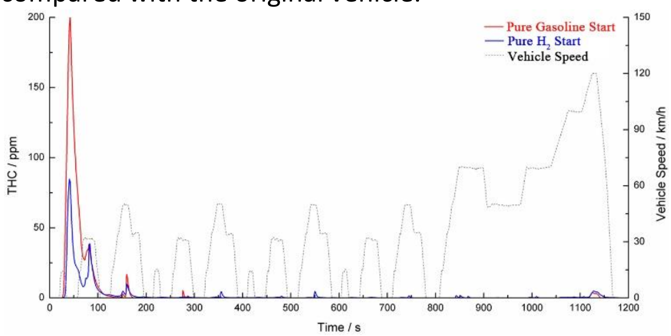

Fig. 4(a) HC emissions

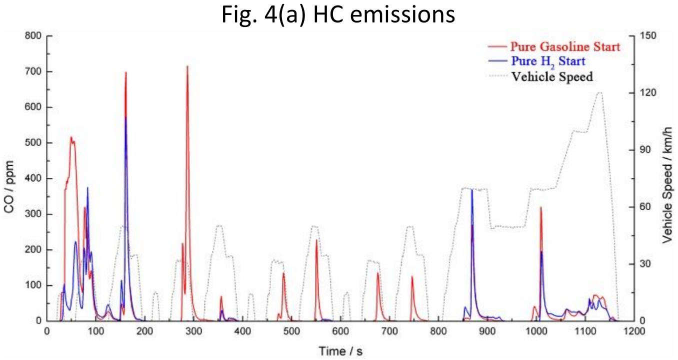

Fig. 4(b) CO emission

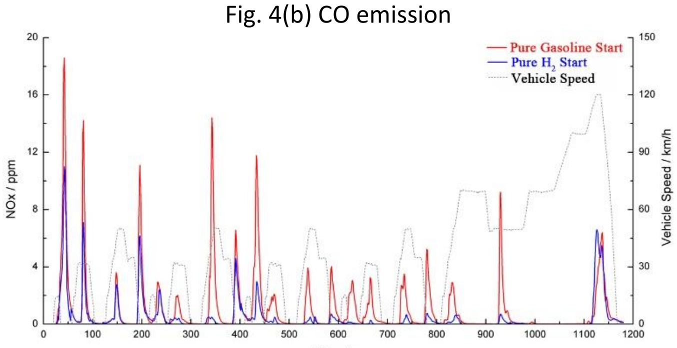

Fig. 4(c) NOx emissions

CONCLUSIONS

This paper developed and tested a PHHV. A plug-in H2 generating system was developed and the control strategy was proposed. It is shown that the HC, CO, NOx and fuel consumption of PHHV were reduced by 57.8%, 52.1%, 10.2% and 12.2% than the original vehicle.

ACKNOWLEDGEMENT

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