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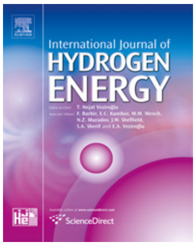

Analysis of the particulate emissions and combustion performance of a direct injection spark ignition engine using hydrogen and gasoline mixtures

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ABSTRACT

Three different fractions (2%, 5%, and 10% of stoichiometric, or 2.38%, 5.92%, and 11.73% by energy fraction) of hydrogen were aspirated into a gasoline direct injection engine under two different load conditions. The base fuel was 65% iso-octane, and 35% toluene by volume fraction. Ignition sweeps were conducted for each operation point. The pressure traces were recorded for further analysis, and the particulate emission size distributions were measured using a Cambustion DMS500. The results indicated a more stable and faster combustion as more hydrogen was blended. Meanwhile, a substantial reduction in particulate emissions was found at the low load condition (more than 95% reduction either in terms of number concentration or mass concentration when blending 10% hydrogen). Some variation in the results occurred at the high load condition, but the particulate emissions were reduced in most cases, especially for nucleation mode particulate matter. Retarding the ignition timing generally reduced the particulate emissions. An engine model was constructed using the Ricardo WAVE package to assist in understanding the data. The simulation reported a higher residual gas fraction at low load, which explained the higher level of cycle-by-cycle variation at the low load.

1. Introduction

As the most recent generation of SI engine, Gasoline Direct Injection (GDI) engines have the potential to achieve a comparable fuel economy to a diesel engine and with a higher power output compared to conventional port fuel injection SI engines. Meanwhile, the ever increasingly stringent emissions legislation (Table 1) has brought some new challenges for GDI engines.

The legislation for Particulate Matter is particularly challenging, both in terms of measurements and in ensuring conformity to legislation. PM emissions are one of the disadvantages of the GDI engine due to the reduced time for fuel-air mixing. The restriction in PM emission applied to diesel engine (6.0×10^{11}/km) might also be applied to GDI engines in the near future. In addition, PM has been found to have adverse effects on human health [5,13], especially for the smaller particles, since they have a higher deposition efficiency in the human respiratory system. SI engines have been found to be the main sources for fine or ultrafine particules [12]. From diesel engine research, it is known that blending hydrogen reduces PM emissions, but no such tests appear to have been reported for GDI engines.

Hydrogen has many attractive intrinsic properties that make it a promising fuel. The lower minimum ignition energy of hydrogen ensures a more stable ignition and eases cold start engine operation, but raises the danger of abnormal

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Table 1 – EU light duty tailpipe emissions requirements for gasoline passenger cars (Designated by European Parliament and European Council, [6]).

Effective timing	CO (g/km)	THC (mg/km)	NMHC (mg/km)	NO_x (mg/km)	PM (mg/km)	PN (1/km)
EU3: 01/2000	2.30	200	n/a	150	n/a	n/a
EU4: 01/2005	1.00	100	n/a	80	n/a	n/a
EU5: 09/2009	1.00	100	68	60	n/a	n/a
EU5b: 10/2011	1.00	100	68	60	5.0/4.5	n/a
EU6: 09/2014	1.00	100	68	60	5.0/4.5	TBD**

Notes: CO: Carbon Monoxide; THC: Total Hydrocarbons; NMHC: Non Methane Hydrocarbons; NO_x: Oxides of Nitrogen; PM: Particulate Matter; PN: Particle Number. TBD: To Be Determined.

combustion. Its high laminar burning velocity (around five times faster than that of gasoline) is expected to increase the indicated efficiency and reduce the cycle-to-cycle variations in combustion. The higher diffusion coefficient of hydrogen may enhance the mixing process, which also can increase the engine efficiency and help to produce less soot and unburned hydrocarbons. Hydrogen also has a smaller quenching distance compared to gasoline, so that the flame can travel further into crevices to ensure more complete combustion. Moreover, adding hydrogen is expected to extend the lean limit due to its lower flammability limit in air. However, the lower net energy density of hydrogen compared with gasoline for a unit volume of stoichiometric mixture with air may reduce the power output. Adding hydrogen also produces a higher adiabatic flame temperature in air, which raises concerns over NO_x emissions. The simulations by using the ISIS (Integrated Spark Ignition engine Simulation), which is a program based on the routines introduced by Ferguson (1986) [7], show that the adiabatic flame temperatures for base fuel, H2, H5, and H10 are 2315K, 2348K, 2350K and 2353K respectively.

2. Literature reviews

Many researchers have investigated the effect of adding hydrogen in a gasoline engine in various ways. Conte and Boulouchos [4] investigated hydrogen-enhanced gasoline stratified charge combustion in GDI engines. They reported a more efficient and stable combustion when adding hydrogen. Moreover, by considering the energy used to produce hydrogen on-board by using a gasoline reformer, they believed the efficiency gains for adding hydrogen were large enough to compensate for the energy used in producing the hydrogen. As for the emissions, higher NO_x emissions were reported. However, by increasing the EGR percentage and delaying the ignition timing at low load or by delaying the ignition timing solely at high load, they achieved a lower NO_x/IMEP ratio compared with operation on pure gasoline and a normal EGR percentage. The unburned hydrocarbons, according to their experimental data, were reduced when adding hydrogen. They suggested that this was due to better combustion stability and having a lower fraction of gasoline in the fuel mixture.

Andrea et al. [2] studied the combustion and emission characteristics of a SI engine when it operated with hydrogen-blended gasoline at lean conditions. They suggested a critical equivalence ratio (λ) of 1.18. When the engine is running at $\lambda < 1.18$, there was no big difference in the torque output and burn rate when adding hydrogen. When $\lambda > 1.18$, torque increased and the burn duration was reduced. As for the emissions, they only investigated the NO emission. When $\lambda = 1$, they found very little difference when adding hydrogen. But as $\lambda > 1.25$, adding hydrogen increased the NO emissions; they attributed this effect to a higher flame temperature. By considering the cost of on-board electrolysis as a method to produce hydrogen, they concluded that the energy gain by adding hydrogen into the gasoline was not sufficient to compensate for the energy used to produce the hydrogen.

As on-board gasoline reforming is becoming a more popular way to produce hydrogen, Suzuki and Sakurai [16] investigated the combustion characteristics of a SI engine fuelled by gasoline and hydrogen or a simulated hydrogen-rich reformer gas (Steam Reforming gas and Autothermal Reforming gas) mixture. They found that the MBT points were retarded significantly as the hydrogen fraction was increased. In addition, the indicated thermal efficiency was found to be higher when the gasoline was blended with hydrogen than when it was blended with steam reforming gases or auto-thermal reforming gases at low load. But at high load, no big difference was reported when various gaseous fuels were blended. Jamal et al. [11] investigated the effectiveness of on-board exhaust gas reforming of gasoline at moderate reformer temperatures (600 and 650 °C). According to their experiments, adding reformed fuel in a gasoline-operated engine could decrease the UBHC and NO_x emissions, increase the overall engine efficiency and smooth the engine operation. However, the hydrogen fractions (up to 4.81% by molar concentration) obtained by exhaust gas reforming at these temperatures are much lower than those predicted by calculations based on Gibbs function minimisation. A new on-board exhaust gas reforming technology (using integrated reformer and Three Way Catalytic converter), which could produce a reformed fuel with higher energy content (up to 11% H_2 by volume fraction), was introduced by Ashur et al. [3]. An overview of hydrogen production technologies was provided by Holladay et al. [9], and a review of on-board generation of hydrogen-rich gaseous fuels was given by Jamal and Wyszynski [10].

The effect of hydrogen addition on knock behaviour is reported by Shinagawa et al. [15]. They found that hydrogen addition can reduce the margin between the ignition timing which caused knock and that for MBT. In addition, the knock behaviour was found to be greatly affected by the distribution of hydrogen, which can be changed by injection direction and injection timings. Knock-free operation at MBT was reported when the hydrogen was unevenly distributed, not only near the wall, but also near the spark plug at 10°BTDC. They concluded that since hydrogen can reduce the