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The Effect of Hydrogen Enrichment on Exhaust Emissions and Thermal Efficiency in a LPG fuelled Engine

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The concept of hydrogen enriched LPG fuelled engine can be essentially characterized as low emissions and reduction of backfire for hydrogen engine. The purpose of study is obtaining low-emission and high-efficiency in LPG engine with hydrogen enrichment. In order to determine the ideal compression ratio, a variable compression ratio single cylinder engine was developed. The objective of this paper is to clarify the effects of hydrogen enriched LPG fuelled engine on exhaust emission, thermal efficiency and performance. The compression ratio of 8 was selected to minimize abnormal combustion. To maintain equal heating value, the amount of LPG was decreased, and hydrogen was gradually added. In a similar manner, the relative air-fuel ratio was increased from 0.8 to 1.3 in increment of 0.1, and the ignition timing was controlled to be at MBT each case.

Key Words : Liquefied Petroleum Gas, Compression Ratio, Minimum Spark Advance for Best Torque, Relative Air-fuel Ratio, Brake Specific Fuel Consumption, Thermal Efficiency

1. Introduction

The automotive engineering has undergone continuous improvements, but at the same time, various global environmental issues related to vehicle use are becoming more serious. With the increasing need both to conserve fossil fuel and to minimize toxic emissions, much effort is being focused on the advancement of current combustion technology. The pollution levels recorded in large urban areas are rising concerns for public health and substantial reductions in pollutant emissions have become an important issue (Heywood, 1988).

California has defined still stricter vehicle emission standards to be phased in over the next decade (Marianne el al., 1999). Vehicle manufacturers must certify each of their vehicles in one of four emissions categories: Transition-Low-Emission Vehicles (TLEV), Low-Emission Vehicles (LEV), Ultra-Low-Emission Vehicles (ULEV), or Zero-Emission Vehicles (ZEV).

Environmental issues such as the global green house effect caused by carbon dioxide and the alternative fuel have been studied. Because of excellent ignitability and high adiabatic flame temperature of hydrogen fuel, the ignition delay

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period, flame development angle, rapid burning angle and overall burning angle in hydrogen fueled engine are remarkably shorter than those of gasoline, diesel engine (Hoekstra et al., 1996).

Hydrogen has much wider limits of flammability in air than methane, propane or gasoline and the minimum ignition energy is about an order of magnitude lower than for other combustibles (Cracknell et al., 2002).

Liquefied petroleum gas (LPG) was assumed to be used in spark ignition engines primarily for its environmental benefits. LPG also offers some petroleum reduction, since approximately 50~60% of the LPG fraction appropriate for motor fuel use currently comes from natural gas. Compressed natural gas (CNG) and LNG which have the potential for reducing emissions of criteria pollutants and greenhouse gases and petroleum use by spark ignition engines (Gerini et al., 1996 ; Lee et al., 2002).

Thomas et al. (1998) described that hydrogen is a primary fuel option under consideration for fuel cell vehicles. The ideal fuel would eliminate local air pollution, substantially bring out greenhouse gas emissions and oil imports, cost no more than current transportation fuels per mile driven, and require little investment in new infrastructure (Min et al., 2002 ; Kim et al., 2001). In addition, the fuel used for future fuel cell vehicles should be suitable for near-term hybrid electric vehicles using internal combustion engines, to avoid the need for introducing more than one new motor fuel in the 21st century. Hydrogen provides the best environmental and economical improvements, but requires the largest infrastructure investment (Lee et al., 1995).

Kim et al. (1995) investigated that performance characteristics of the hydrogen fueled engine with respect to several variables such as spark timing, air-fuel equivalence ratio, and engine speed were analyzed and compared with those of gasoline engine. It was found that qualitative trend of the engine performance of engines was similar while quantitative characteristics as to spark timing, torque, and cyclic variation of hydrogen fueled engine were different from those of gasoline engine (Han et al., 1995).

The objective of this paper is to clarify the effects of hydrogen enriched LPG fuelled engine on exhaust emission, thermal efficiency and performance. The concept of hydrogen enriched LPG fuelled engine can be essentially characterized as low emissions and reduction of backfire for hydrogen engine. A high accuracy heavy-duty variable compression ratio single cylinder engine (VCSCE) was manufactured to investigate its performance and emissions characteristics.

2. Experimental Apparatus and Method

Figure 1 shows the schematic diagram of the experimental apparatus. The engine was coupled to a dynamometer to control the engine speed and load. Oil temperature, coolant temperature, exhaust temperature, inlet pressure and exhaust pressure were measured with various sensors. The exhaust gas constituents (CO, CO_2, THC, O_2, NOx) were measured by a gas analyzer (Mexa 9100DEGR, Horiba).

Signals from the CPS (Crankshaft Position Sensor) installed on the crankshaft pulley and the hall sensor installed on the cam-shaft pulley are sent to the ignition control device, which then determines the amount of electric energy to be sent to the combustion chamber and controls the ignition timing.

In order to determine the ideal compression ratio, the experimental engine was developed. The VCSCE (variable compression ratio single cylinder engine) used in this experiment was

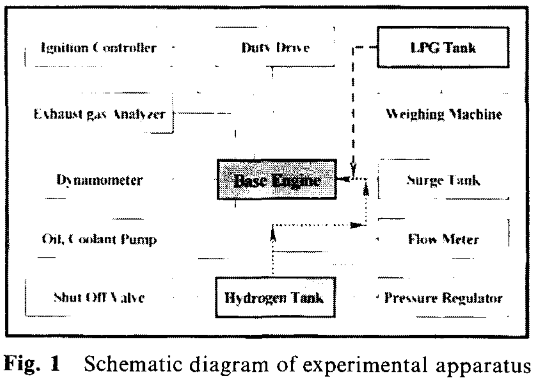

Fig. 1 Schematic diagram of experimental apparatus

Table 1 Specifications of test engine

Engine Type		OHV
Number of Cylinder		1
Bore		130 mm
Stroke		140 mm
Displacement		1,858.2 cc
Range of Compression Ratio		7~14
Intake Valve	Open	BTDC 18°
	Close	ABDC 50°
Exhaust Valve	Open	BTDC 50°
	Close	ATDC 18°
Iding RPM		600
Valve Clearance		0.4 mm at Intake
		0.6 mm at Exhaust
Number of Balance Shaft		2
Length of Connecting Rod		260 mm

based on a 6 cylinder 12L diesel engine that had been modified into a single cylinder spark ignition engine. Major steps in the engine's fabrication are outlined below, and the specifications are listed in Table 1.

i) The cylinder head was altered so that a spark plug could be inserted in the place of the injection nozzle, and the piston was modified into a bath tub type. In order to take advantage of the squish effect that occurs at the end of the compression process and subsequently optimize the mixture formation, a bath tub type piston was made.

ii) New crankshaft and crankcase were developed. A new flywheel was made so that the desired RPM could be obtained (Park, 1996).

iii) A balance shaft and a flywheel were made to minimize vibration and acceleration, and the cooling and lubricant systems were placed externally in order to precisely determine engine performance.

All experiments were conducted at 1400 RPM, MBT (Minimum spark advance for Best Torque), WOT (Wide Open Throttle), and a compression ratio of 8. The compression ratio of 8 was selected to minimize abnormal combustion. Upon determining the normal operation of the engine, LPG was supplied to achieve a relative air-fuel ratio of

Table 2 Characteristics of LPG and hydrogen

	C_4H_{10}	H_2
Theoretical Air-fuel Ratio	15.5	34.3
Lower Heating Value (MJ/Kg)	45.84	120
Flammmability Limits	0.4~1.7	0.12~10.12
Density (Kg/m^3)	2.64	0.0899
Adiabatic Flame Temperature (℃)	≒1990	2384
Turbulent Burning Velocity (m/s)	≒0.4	1.7
Autoignition Temperature (℃)	585	450

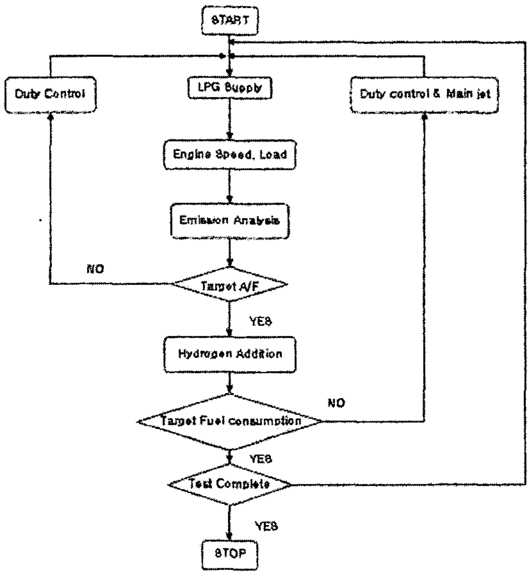

Fig. 2 Flowchart for relative air-fuel ratio measurment

0.8. To maintain equal heating value, the amount of LPG was decreased, and hydrogen was gradually added. In a similar manner, the relative air-fuel ratio was increased from 0.8 to 1.3 in increment of 0.1, and the ignition timing was controlled to be at MBT each case. The characteristics of LPG and hydrogen are listed in Table 2.

A desired mixture of LPG and hydrogen was used as the fuel system, and the fuel rate was controlled with a duty drive and a solenoid valve. LPG consumption was measured via a balance scale with a degree of precision of 1 g. High purity hydrogen at 200 bar was flown through the pressure controller, the mass flow meter, the solenoid valve, and the flame arrestor on its way to the intake. Figures 2 and 3 show the flowchart for

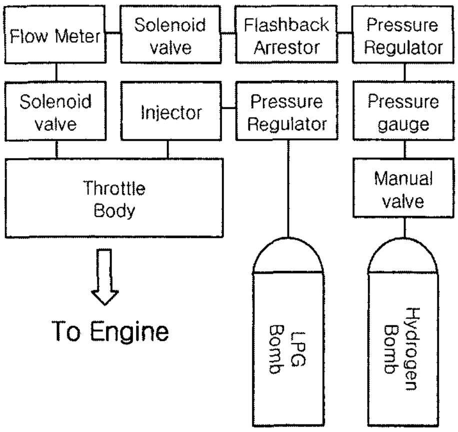

Fig. 3 The fuel supply system

more accurately determining the relative air-fuel ratio and the fuel supply system, respectively. As seen in the figures, if the relative air-fuel ratio and the LPG consumption rate do not reach target values, the duty and main jet are controlled accordingly.

3. Results and Discussions

3.1 Motoring test and pressure diagram

Figure 4 shows the cylinder pressure diagram at 1400 RPM, MBT, and a compression ratio of 8. Figure 5 shows the theoretical cylinder pressure at different specific heat ratios and experimental cylinder pressure versus crank angle at the motoring condition. Overall, this figure shows similar trends between the pressure diagram taken from simulation and the experimental pressure. Also, it can be deduced that there is no leakage in the manufactured engine. The cylinder pressure curve at BTDC (before top dead center) tends to be a little low and the pressure curve at ATDC (after top dead center) tends to be a little high because it is thought that the effective compression ratio becomes low as the closing of the inlet valve is accomplished at ATDC.

3.2 CO emission

Figure 6 shows CO emission as a function of relative air-fuel ratio with the addition of 0%, 10% and 20% H_2 at 1400 RPM, MBT, WOT and a compression ratio 8. The CO emission decreases

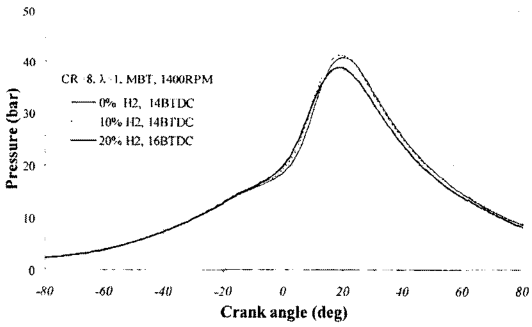

Fig. 4 Cylinder pressure versus crank angle at 1400 RPM, MBT, and a compression ratio of 8 with various H_2 proportions

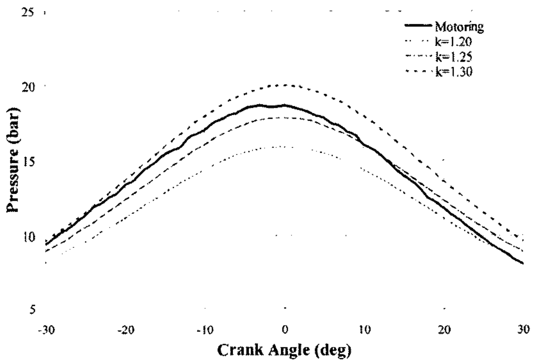

Fig. 5 Cylinder pressure versus crank angle at different specific heat ratios and motoring condition

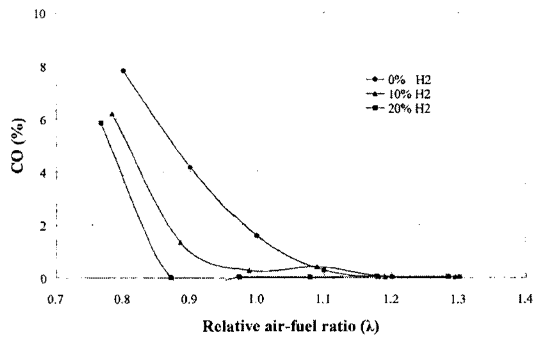

Fig. 6 CO emission versus relative air-fuel ratio for different hydrogen rates

if the relative air-fuel ratio (λ) is increased from 0.8 to 1.3, and the CO emission also decreases as hydrogen is added. For rich relative air-fuel ratios around λ=0.8, CO emission exhibits a maximum value, and it appears that there is almost zero CO emission above $\lambda=1.2$. The figure shows that a great quantity of CO emission is produced with the rich air-fuel mixture, since insufficient supply of air prevents all carbon of the fuel from becoming the perfect combustion gas CO_2. Therefore, CO emission can be represented as a function of the relative air-fuel ratio.

3.3 Total hydrocarbon (THC) emission

THC emissions from quench regions in cylinder are expelled during the exhaust process. With slightly lean mixtures, although the quench zone is large, the excess oxygen oxidizes much of the THC emissions when they are mixed later in the exhaust system. With very lean mixtures, combustion generally becomes erratic and the amount of THC emissions increases.

Figure 7 shows THC emission as a function of relative air-fuel ratio with the addition of 0%, 10% and 20% H_2 at 1400 RPM, MBT, WOT and a compression ratio of 8. THC emissions tends to be similar to CO emission at rich mixture conditions as the relative air-fuel ratio is increased from 0.8 to 1.3, but it is increased on the lean side. THC emissions on the rich side also decrease with the addition of hydrogen. The THC emissions decrease, when LPG fuel supply decreases. As shown in the figure, in rich and around theoretical air-fuel ratio zone, the THC emissions are much affected by the lack of oxygen.

3.4 NOx emission

Figure 8 shows NOx emission as a function of relative air-fuel ratio with the addition of 0%, 10% and 20% H_2 at 1400 RPM, MBT, WOT and a compression ratio of 8. In this figure, NOx emission is the maximum at about $\lambda=1$, and the addition of 20% hydrogen results in a 40% increase in the amount of NOx emission compared to that of pure LPG combustion. This fact results from the fast combustion of hydrogen fuel and the higher maximum temperature and pressure in the cylinder compared to LPG combustion.

3.5 Thermal efficiency and fuel consumption

Figure 9 shows thermal efficiency as a function of relative air-fuel ratio. As shown in this figure, thermal efficiency increases with the addition of hydrogen. At $\lambda=1$, thermal efficiency was increased by about 5% with the addition of 10~20% hydrogen. The reason for this increase in thermal efficiency was that the hydrogen fuel burns all at once.

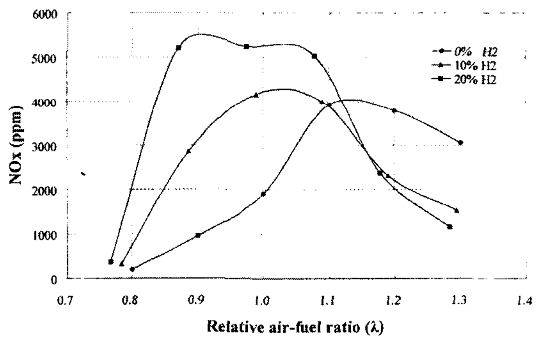

Fig. 8 NOx emission versus relative air-fuel ratio for hydrogen rates

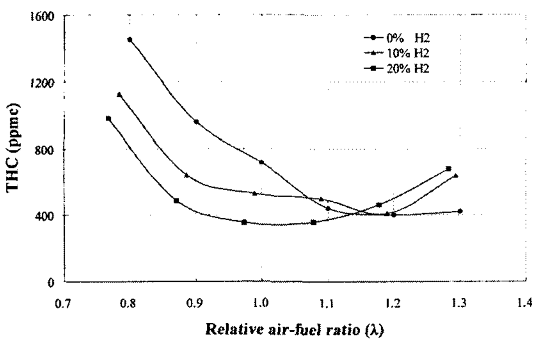

Fig. 7 Total hydrocarbon emission versus relatives air-fuel ratio for hydrogen rates

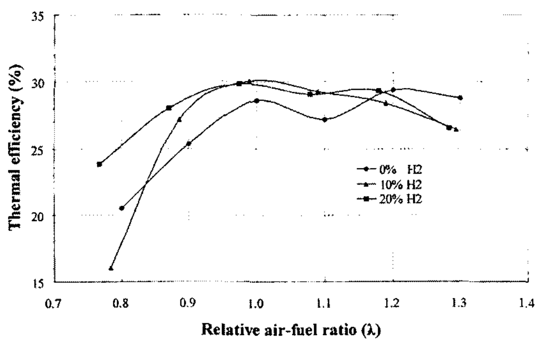

Fig. 9 Thermal efficiency versus relative air-fuel ratio for the addition hydrogen

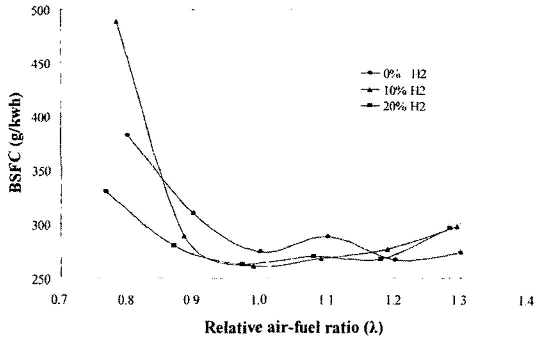

Fig. 10 Fuel consumption versus relative air-fuel ratio for the addition of hydrogen

Figure 10 shows fuel consumption as a function of relative air-fuel ratio with the addition of 0%, 10% and 20% H_2 at 1400 RPM, MBT, WOT and a compression ratio of 8. Fuel consumption that depends on thermal efficiency is defined as the mass flow rate per hour, and it may depend on the increase of brake power rather than the increase of fuel quantity. The reason for lower fuel consumption with increased hydrogen additions compared to LPG combustion would be the fast flame propagation velocity of hydrogen.

4. Conclusions

The objective of this paper is to clarify the effects of a hydrogen enriched LPG fuelled engine on exhaust emission, thermal efficiency and performance. A high accuracy heavy-duty variable compression ratio single cylinder engine (VCSCE) was manufactured to investigate its performance and emissions characteristics. The results obtained are as follows.

(1) CO emission decreases if the relative air-fuel ratio (λ) is increased from 0.8 to 1.3, and the CO emission also decreases as hydrogen is added. CO emission can be represented as a function of the relative air-fuel ratio.

(2) THC emission tends to be similar to CO emission at rich mixture conditions as the relative air-fuel ratio is increased from 0.8 to 1.3, but it is increased on the lean side. THC emission on the rich side also decrease with the addition of hydrogen.

(3) NOx emission is the maximum at about $\lambda=1$, and the addition of 20% hydrogen results in a 40% increase in the amount of NOx emission compared to that of pure LPG combustion. This fact results from the fast combustion of hydrogen fuel and the higher maximum temperature and pressure in the cylinder compared to LPG combustion.

(4) Thermal efficiency increases with the addition of hydrogen. At $\lambda=1$, thermal efficiency was increased by about 5% with the addition of 10~20% hydrogen. The reason for this increase in thermal efficiency was that the hydrogen fuel burns all at once.

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