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DEVELOPMENT ON ENHANCED LEAKED FUEL RECIRCULATION DEVICE OF LPLi ENGINE TO SATISFY SULEV STANDARD

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ABSTRACT−The liquefied petroleum gas (LPG), mixture of propane and butane, has the potential to reduce toxic hydrocarbon emissions and inhibit ozone formation due to its chemical composition. Conventional mixer systems, however, have problems in meeting the future lower emission standards because of the difficulty in controlling air-fuel ratio precisely according to mileage tar accumulation. Liquid Phase LPG injection (LPLi) system has several advantages in more precise fuel metering and higher engine performance than those of the conventional mixer type. On the other hands, leakage problem of LPLi system at the injector tip is a main obstacle for meeting more stringent future emission regulations because these phenomena might cause excessive amount of THC emission during cold and hot restart phase. The main focus of this paper is the development of a leaked fuel recirculation system, which can eliminate the leaked fuel at the intake system with the activated carbon canister. Leaked fuel level was evaluated by using a fast response THC analyzer and gas chromatography. The result shows that THC concentration during cold and hot restart stage decreases by over 60%, and recirculation system is an effective method to meet the SULEV standard of the LPLi engine.

KEY WORDS : Liquid Phase LPG injection, Leaked fuel recirculation system, Activated carbon, Fast response THC analyzer, Gas chromatography, SULEV, Zero evaporative emissions

1. INTRODUCTION

Recently, further and stricter emissions regulations such as SULEV (Super Ultra Low Emission Vehicle) and Euro-IV have been introduced to reduce automotive emissions. Much more attention, therefore, has been given to the development of alternative automotive fuels, such as LPG (Liquefied Petroleum Gas) and CNG (Compressed Natural Gas), by car makers. The advantages of LPG are potential emission reduction and low fuel price over gasoline (Yamaguchi *et al.*, 2003). On the other hands, the conventional fuel supply system of an LPG engine uses a vaporizer and mixer to adjust the fuel supply quantity, which has difficulty in precisely adjusting the air-fuel ratio. The LPLi system injects liquid phase LPG to each intake ports by using the MPI (Multi Point Injection) system (Gerini *et al.*, 1996). This electronic controlled system has advantages in the increment of engine power and reduction of exhaust emissions over the conventional FBM (Feed-back Mixer) type. However, leaked LPG fuel from injector tips after engine stop might produce excessive THC emission during cold and hot restart phases. The leakage mechanism of the LPLi system is as follows. Firstly, the fuel temperature in a fuel supply system is slowly increased by heat transfer from the engine coolant and oil after engine operation (Matsushima *et al.*, 2000; Heywood, 1989; Kishi *et al.*, 1999; Lee and Daisho, 2004). Secondly, the vaporized LPG in the fuel rail is leaked through the injector gap and tip. Finally, this leaked fuel produces a rich mixture resulting in excessive amount of THC emission during engine restart condition (Itakura *et al.*, 2000; Siegl, 2000). In this context, several methods are suggested for reduction of the THC emission during the staring phases. One is fundamental exclusion of the tip leakage through the improvement of injector itself, the other is removal of unburned THC through the combustion process controlled by the engine management system, and the third is elimination of the leaked fuel through adsorption in the intake system. In case of the third method, an additional active system is necessary to recirculate the vaporized LPG in the intake manifold. The main works of this study are as follow: (1) The leakage fuel recirculation device with an activated carbon canister is developed; (2) THC reduction rate is evaluated by a fast response THC analyzer during restart cranking case; (3) The working performance of the activated carbon canister is estimated by specially designed rig. The main result showed that THC reduction rate reached over 60% during cranking with the leakage fuel recirculation

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Corresponding author. e-mail: spark@korea.ac.kr system of an LPLi engine. Consequently, active leakage fuel recirculation was found to be a remarkably effective device for meeting the SULEV target including zero evaporative emissions.

2. TEST EQUIPMENT AND METHOD

2.1. Experimental Equipment

Figure 1 shows the schematic diagram of an LPLi engine and fuel supply system. Liquid phase LPG in the fuel tank is supplied into the fuel rail through the external fuel pump. The injector of the LPLi is a bottom feed type, which enables the reduction of the vapor lock of LPG fuel. Injection pressure is constantly controlled by the downstream pressure regulator up to Δp 5 bar of LPG fuel tank and maintained through the fuel supply line. Because the LPG phase of the fuel rail is affected by the pressure and temperature of the fuel, the compensation logic for various fuel temperature and pressure fluctuation was developed to control the air-fuel ratio precisely. Combustion phenomena were analyzed by using the combustion analyzer and spark plug type pressure sensor was installed in the combustion chamber. High speed THC analyzer (CAMBUSTION HFR 400) was used for measurement of the cyclic-to-cycle THC at the exhaust port. THC sampling probes of the high speed THC analyzer were mounted on the outlet of the exhaust port. Table 1 shows the specifications of the test engine. Displacement of the test engine is 3.0 liter, V6 type and compression ratio is 8.9. A special electronic control unit (ECU) for LPLi was developed to adjust the injection timing and spark timing. A voltage driven injector driver module is installed at the ECU for the precise control of the LPG injection. The exhaust system consists of UCC with MCC.

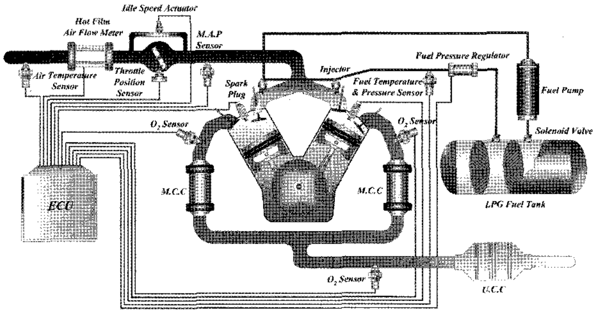

Figure 1. Schematic diagram of LPLi engine.

Table 1. Specifications of test engine.

Engine	LPG V6, SOHC
Displacement	2,972 cc
Compression ratio	8.9 : 1
Fuel control	MPI with injector driver module
Fuel system	Fuel Pump, Pressure Regulator Pressure & Temperature sensor

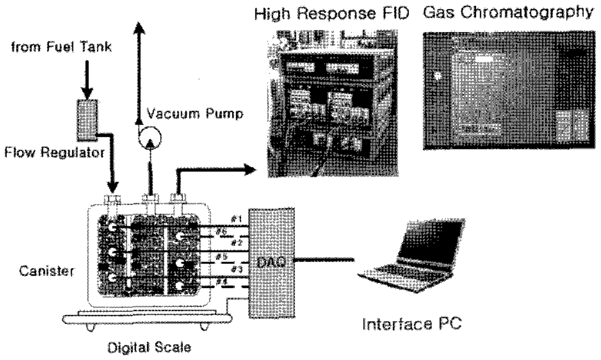

Figure 2. Schematic diagram of canister rig test equipment.

2.2. Rig Test Equipment

Figure 2 shows the test rig equipment used to measure the working capacity of activated carbon. LPG fuel is supplied from the fuel tank into the canister through a gas port by using a flow meter and a solenoid valve to maintain a constant flow rate. And the adsorbed LPG fuel is purged through the recirculation port on canister by the vacuum pump. Thermocouples are installed in the canister to measure the temperature distribution and check dead zones during the adsorption process. Working capacity of the canister is measured by the digital scale. Table 2 shows the properties of activated carbons. Bulk density designates the mass of the charged carbon per unit volume. In addition, the porosity of activated carbon is defined as follows:

$$Porosity = (V - V_S)/V \tag{1}$$

V : Total volume including void of activated carbon
Vs : Void volume between activated carbon particle

Figure 3 represents the schematic structure of activated carbon. The pore size of the activated carbon is classified into macro (over 500 Å), meso (20–50 Å) and micro one

Table 2. Properties of activated carbon.

Properties	Units	Activated carbon	
		Pellet	Granular
		3GX	6×8 size
Bulk density	g/mL	0.36–0.38	0.32–0.42
Porosity	%	62–65	58–68
Working Capacity (Butane)	g/dL	15.0	11.4

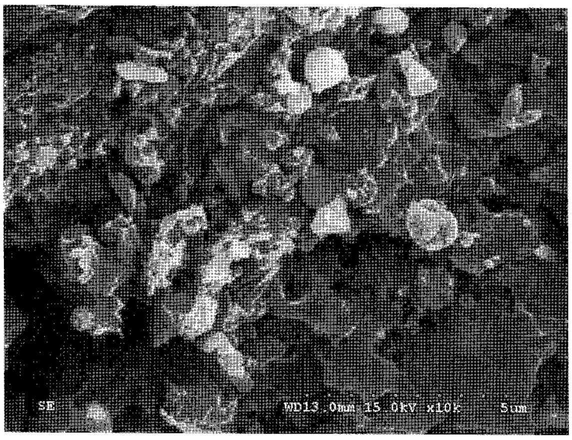

Figure 3. Structure of activated carbon.

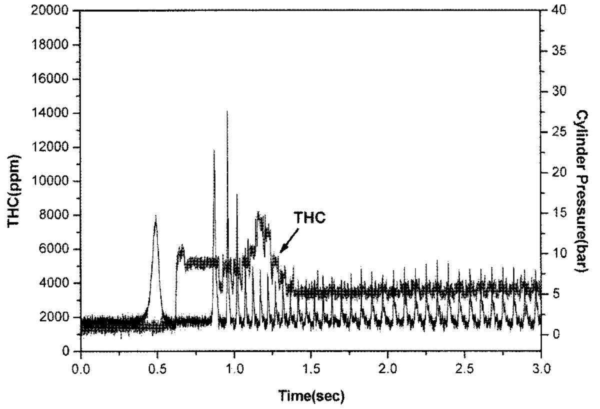

Figure 5. THC and cylinder pressure during start phase with leakage fuel purge using compressed air.

(below 20 Å). Gas and liquid phase of the HC components are adsorbed onto various pore sites. Generally, activated carbon with large amounts of the micro pore shows higher adsorption working capacity while lower desorption efficiency.

3. TEST RESULTS AND DISCUSSION

Figure 4 shows the engine-out THC level during start phase without leakage fuel purge. Engine was operated until its coolant temperature reached 90°C before the engine was stopped and soaked for 30 minutes. Cyclic THC and cylinder pressure of the LPLi engine was analyzed by the fast response THC analyzer and combustion analyzer. The THC level of the start phase reached about 13,000 ppm without the intake and exhaust system purge.

Compared to the THC level of without leakage fuel purge case, the maximum THC emission reached only 5,000 ppm. This result means that the fuel leakage phenomena at the fuel system is observed after engine stop and the leakage fuel adsorption method is very effective measure to reduced the large amount of THC during start phase of LPLi engine.

Figure 6 shows the working capacities of pellet and granular types of activated carbon. Fuel flow rate into canister is fixed and digital scale is used for the measurement of mass variation in the canister. As shown in Figure 2, several baffles are installed in the flow passage of the canister to increase the adsorption capacity. Test results show that 1 baffle canister filled with pellet type activated carbon can adsorb about 20–35 g of LPG fuel (3 baffle canister: 45 g) and granular type activated carbon is about 15–20 g (3 baffle canister: 20–35 g). This result means that the pellet type activated carbon is more effective to adsorb a leaked fuel than the granular one because of its higher working capacity.

Exothermal reaction is accompanied by adsorption of LPG fuel in the canister. Therefore, temperature variation and working capacity of the canister are very closely

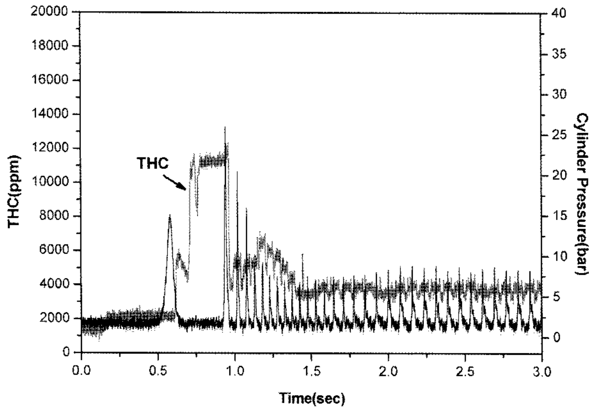

Figure 4. shows the THC level with leakage fuel purge using compressed air just before engine start.

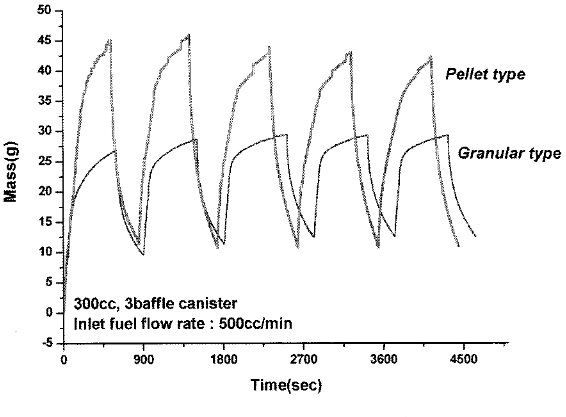

Figure 6. Comparison of working capacity.

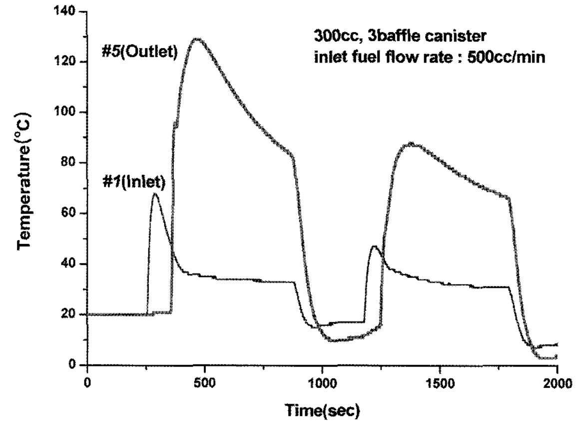

Figure 7. Comparison of temperature variation of activated carbon canister.

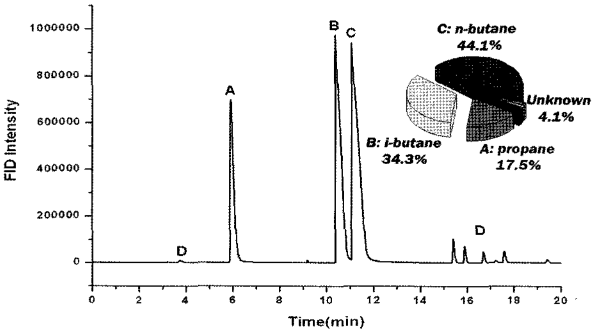

Figure 8. GC Chromatogram of winter season LPG.

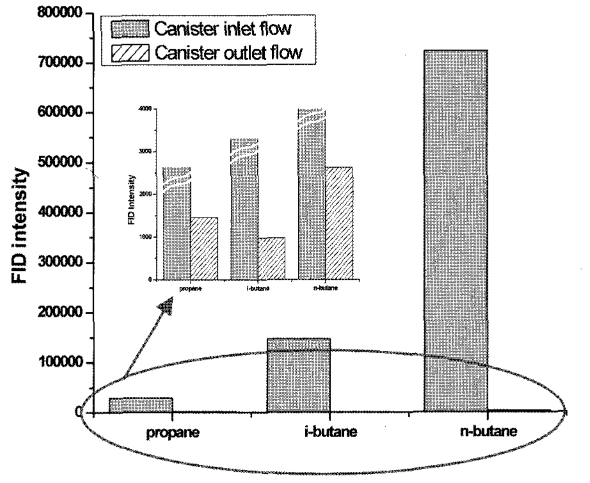

Figure 9. Comparison of individual HC level inlet and outlet port of canister (10 seconds after adsorption).

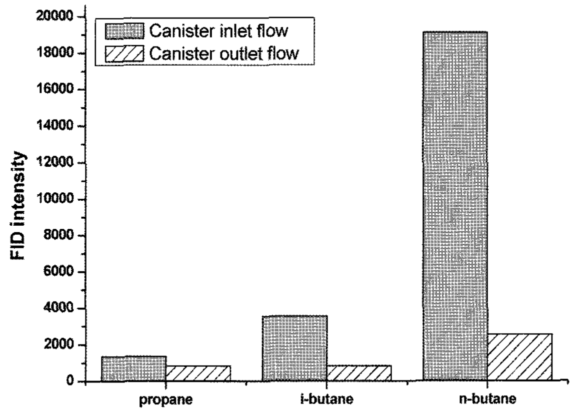

Figure 10. Comparison of individual HC level inlet and outlet port of canister (3 minutes after adsorption).

related with each other. Figure 7 represents the temperature distribution of the canister at points #1 and #5 as shown in Figure 2. The point #5 has a higher temperature than point #1 because the point #1 is close to the gas inlet port. From this result, the optimized canister design with respect to geometry, baffle and carbon material, is needed to avoid the dead zone.

LPG is mainly composed of propane (C_3H_8) and butane (C_4H_{10}). Fuel composition in Korea is varied with the seasons to improve the startability of LPG vehicles. LPG fuel at summer consists of at least 98% butane while propane is added to winter season LPG (up to 20–25%). This study mainly analyzed and tested LPG fuel for winter. GC was used for the determination for the adsorption efficiency of each composition. Figure 8 shows the chromatogram and composition of winter season LPG in Korea. HP-5890 Series-II GC, capillary column of HP-PLOT Al_2O_3 (50 m×0.53 mm×15 μm) and FID (Flame Ionization Detector) were used for analysis.

Figure 9 indicates that more than 95% of the inlet propane and 99% of butane are adsorbed in the canister after 10 seconds. Figure 10 shows the adsorption efficiency of each fuel component after 3 minutes. The adsorption efficiency of n-butane is reached to 87%, and that of i-butane is 76% compared to 10 seconds case. Especially, the adsorption efficiency of propane drops rapidly to 40%. To increase the adsorption efficiency of propane, more research on the advanced activated carbon material is required.

Leakage fuel in the intake system exists as an air-fuel mixture. So its volume is much spacious than the canister. To improve the adsorption efficiency of the recirculation system, air should be discharged through the air port continuously. Fuel components in the discharging air should be minimized for system performance and evaporative emission.

Figure 11 shows the THC concentration at the canister air port. The THC level of exhaust air is measured by a high response THC analyzer. When the air port is under normal open condition, THC level is measured about 100 ppm. This can be decreased to 30 ppm using duty control logic with 10 Hz and 50% duty.

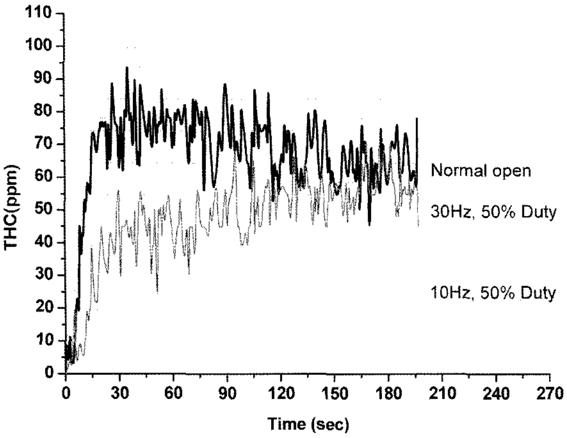

Figure 11. THC level at air port with solenoid duty.

Because the vaporization of LPG fuel is very high compared to that of gasoline, the diffusive distribution at the intake system of leaked fuel was analyzed by GC. A small amount of leaked fuel around LPLi injectors and air cleaner was supplied into the GC to minimize the sample loss. After engine operation was stopped, the intake system was purged by using compressed air to eliminate the influences of residual gas and fuel.

Figures 12 and 13 show the individual HC components of leaked fuel around the injector and air cleaner with analysis time. Test results show that the leaked fuel components around injector, such as propane, i-butane and n-butane, reach the maximum concentration at 60 minutes and gradually decrease as the engine coolant temperature drops. Especially, the leaked fuel components were diffused into the air cleaner side, and the trend of THC generation shows similar results. From this result, the adsorption timing of leakage fuel recirculation system is a critical factor to adsorb the leaked fuel of LPLi engine.

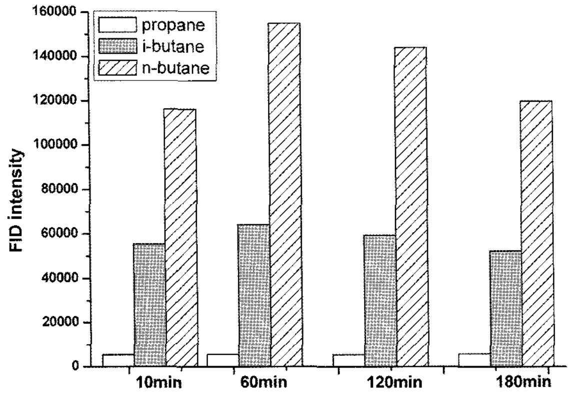

Figure 12. Leaked fuel concentration around injector.

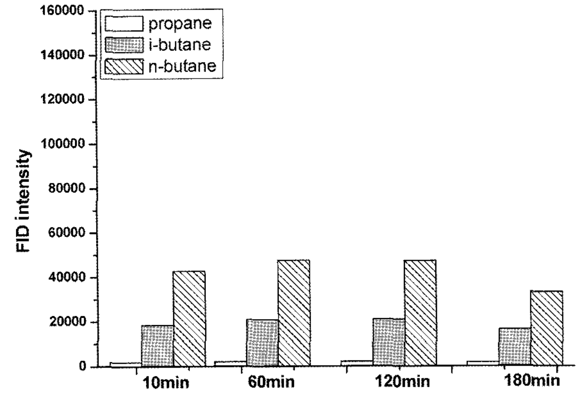

Figure 13. Leaked fuel concentration around air cleaner.

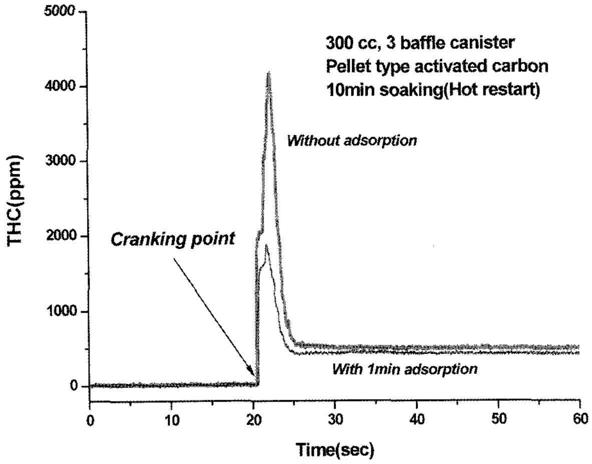

Figure 14. THC reduction during hot restart (soaking time: 10 minutes).

To quantify the effectiveness of a leakage fuel recirculation system on THC reduction at hot and cold start, the high response THC analyzer was installed at exhaust pipe of an LPLi engine. Engine was operated until its coolant temperature reached 90°C before engine stop and was soaked for 10 minutes and 13 hours, respectively. In this test, the fuel injection signal and ignition signal were cut off to prevent fuel injection and combustion.

Figure 14 shows the effect of fuel adsorption on THC reduction during engine cranking after 10 minutes soaking time. THC concentration level without adsorption reached about 4,300 ppm, and about 2,000 ppm with leakage fuel adsorption.

Figure 15 represents the accumulated THC concentration during cranking with the recirculation system. Accumulated THC reduction rate reached about 54%.

Figure 16 shows the effect of fuel adsorption on THC reduction during engine cranking after 13 hours soaking time. THC concentration level of 13,000 ppm without adsorption decreased to 5,100 ppm with fuel adsorption.

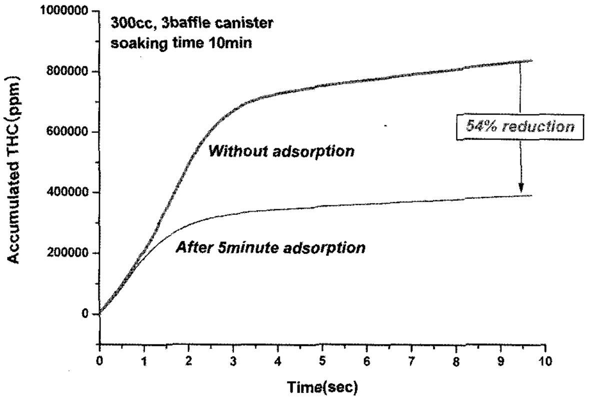

Figure 15. Accumulated THC reduction rate during hot restart (soaking time 10 minutes).

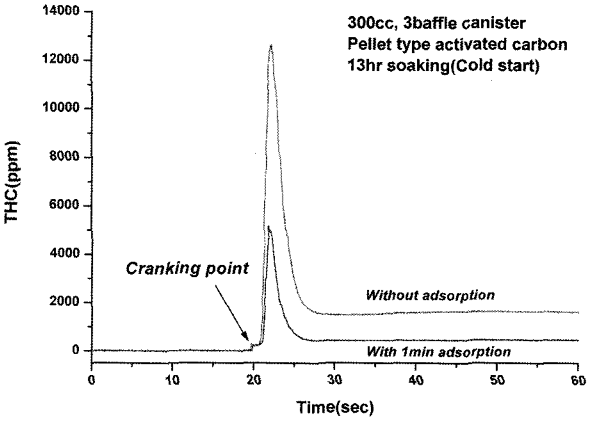

Figure 16. THC reduction during cold start (soaking time: 13 hours).

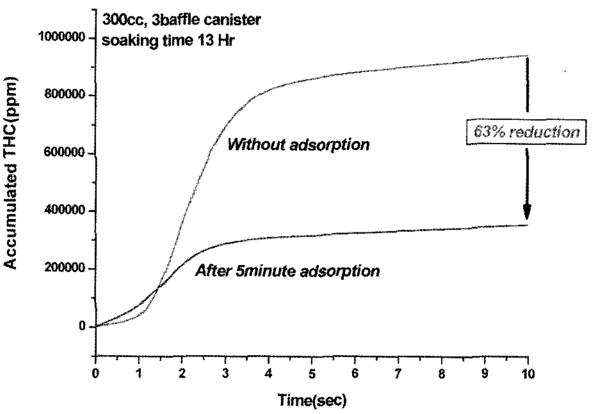

Figure 17. Accumulated THC reduction rate during cold start (soaking time: 13 hours).

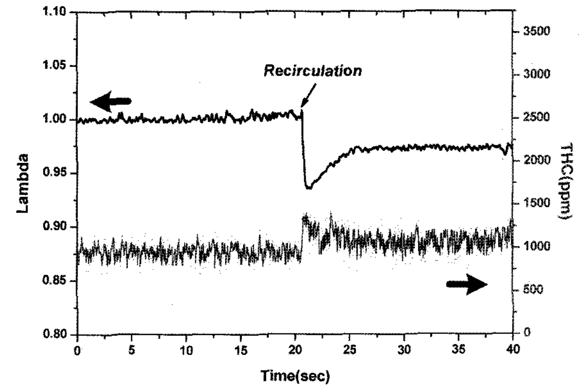

Figure 18. Lambda and THC variation with leakage fuel recirculation (recirculation port is normally opened).

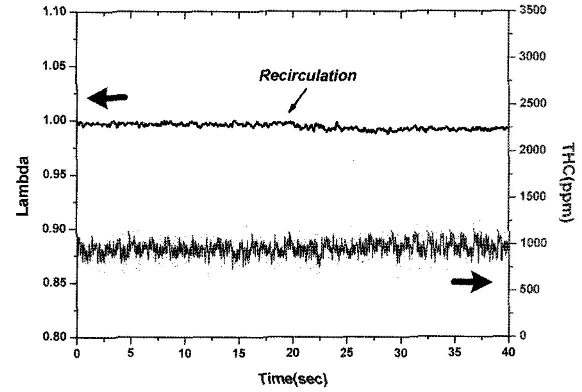

Figure 19. Lambda and THC variation with leakage fuel recirculation (recirculation port is duty controlled, 5Hz 5% duty).

Accumulated THC reduction rate after 13 hours soaking time reached about 63% as shown in Figure 17. These results show that the leakage fuel adsorption system is a very effective measure for reducing the THC concentration at cold and hot restart operation.

Adsorbed fuel in the canister is easily recirculated into the intake manifold by the intake vacuum pressure during engine operation. But, this additional fuel influences on the combustion stability, lambda closed loop, and exhaust emissions. Engine test has been performed to confirm the effectiveness of a fuel recirculation system on engine performance and emission characteristics. Generally, recirculation at low coolant temperature of the adsorbed fuel significantly influences engine stability than at the engine warmed up condition. In addition, fuel recirculation at idle is worse than that at part load operation. In this test, adsorbed fuel in the canister is supplied into the intake manifold at 1800 rpm, 2.0 bar BMEP at the fully warmed up condition. Recirculation is undertaken on the upstream of the intake ports by using the stainless delivery line.

Figure 18 shows the lambda and THC variation with leakage fuel recirculation, which has the normally opened recirculation port. Lambda is maintained around stoichiometric air-fuel ratio before fuel recirculation. The air-fuel ratio suddenly dropped to 0.95 and the THC emission increased with additional fuel supplement.

Figure 19 shows the lambda and THC variation with leakage fuel recirculation of which recirculation port is duty controlled. In this case, the solenoid valve which was installed on the recirculation port was controlled with 5Hz and 5% duty to decrease the flow rate of the recirculation fuel. Lambda of LPLi engine and THC concentration level of exhaust gas were stabilized by controlling the fuel supplement rate. In order to make sure of the engine stability and low emission, advanced logic was absolutely required to control the precise flow rate of the recirculation system.

4. CONCLUSIONS

From the study of the THC reduction in an LPLi engine with the recirculation system, followings are concluded.

(1) Pellet type activated carbon was more effective in adsorbing leakage fuel because of its higher working capacity than granular one.

(2) By increment of baffle numbers in the canister flow passage, three baffled pellet type canister of 300 cc capacity could adsorb about 45 g of LPG fuel. And 20–35 g of LPG fuel was adsorbed in a three baffled granular type canister with 300cc volume.

(3) More than 95% of inlet propane and 99% of butane were adsorbed in the canister after 10 seconds from adsorption start. But, 3 minutes later, the adsorption efficiencies of n-butane and i-butane decreased to 87% and 76% respectively. Especially propane decreased to 40%.

(4) In normal open condition, THC level was 100 ppm in exhaust air from the canister air port. This level can be reduced to 30 ppm by using suitable duty control

(5) The leakage fuel adsorption system reduced the THC level from 13,000 ppm to 5,100 ppm in peak to peak base, in which total accumulated THC reduction rate was 63%.

(6) Rich spike of the air-fuel ratio during re-entering stage of absorbed fuel was stabilized by the decrease in the fuel supplement rate through the duty control logic.

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