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Effects of Spark Ignition Timing and Fuel Injection Strategy for Combustion Stability on HEV Powertrain during Engine Restart and Deceleration Driving

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Abstract: Stringent regulations of exhaust emission and fuel economy from vehicles have become major issues in the automotive industry. Hybrid Electric Vehicle (HEV) can be one of the crucial alternative plans over current conventional vehicle, but they have drawbacks such as the increase of engine out total hydrocarbon (THC) emission and the deterioration of combustion stability at frequent engine stop and restart. This study performs experimental investigation to obtain a better understanding of THC emission characteristic at engine restart and deceleration driving on a HEV powertrain of parallel motor/generator type using a Fast response Flame Ionization Detector (FFID) and specified tool for cycle by cycle, cylinder to cylinder combustion and engine control characteristic analysis during transient state of HEV powertrain. The experimental conditions cover variation of high voltage battery State of Charge (SoC), spark ignition timing and injected fuel mass. As an experimental result, the effect of the spark timing control is so little, but the reasonable injection duration for stable combustion is more than 7 (ms) at the first cycle shortly after engine start-up by motor although the injection rate is 2.7 ~ 3 (ms) at idle state. The reason why more fuel was injected was that the deposited fuel in the cylinder and intake port was reduced due to discharging and vaporization during deceleration step before idle stop.

1. INTRODUCTION

Recently, there has been a growing interest in environmental issues along with the concerns raised about the shortage and high cost of natural resources worldwide. Furthermore, as consumer demands on automotive vehicles have become ever more complicated and diversified; the development of a high performance, high fuel economy and low emission vehicle is recognized by the automotive industry as essential thereby resulting in high investment and technological development efforts. Among such efforts, one of the most plausible means that can be used to promote the decrease in fuel consumption and exhaust gas emission is the development of hybrid vehicle technologies that operate on both the conventional internal combustion engine and electric power source, hence distributing the each power source effectively. Hybrid vehicles can promote the fuel economy using idle engine stop function, downsizing the engine and storing the thrown mechanical or resistive energy into battery power source during deceleration deriving. It can also achieve higher acceleration performance through the motor acting as supplementary power than one of the conventional vehicle.

However, despite the advantage of fuel economy due to reduced fuel consumption using idle stop function, there are some related issues which are the problem of significant emission of unburned HC due to misfire or partial burning for engine restart by motor after idle stop. Theses also probably affect passenger comfort since the unstable combustion of engine causes a sudden change in power output, engine vibration and increased noise.

The methods for discerning whether there are proper combustion in the engine or not have introduced from previous researches. For example, there are not only measurements of the change in engine torque or the angle velocity of the crank shaft but also determinations of the indicated mean effect pressure (IMEP) using the cylinder pressure transducers. However, in case of the former method, its main disadvantage is that it is hard to establish the standard for generation of misfire or partial burning due to cylinder variation and to check precisely in which cylinder misfire has occurred. Furthermore, the latter method is limited to quantitative analysis of engine out THC rate.

In this study, hence, in order to indicate how much include the unburned hydrocarbon in exhaust gas and where cylinder abnormal combustion has occurred, the fast respond Flame Ionization Detector (FFID), the piezoelectric pressure transducers and specified analysis tools are engaged. Two sampling probes of the FFID were installed as close as possible not only to exhaust manifold (Tailpipe) where the exhaust gas is collected but also to the number one cylinder exhaust valve. Four pressure transducers were equipped with spark plug adapter. Additionally, the specified analysis system was developed using PXI-8196 and LabVIEW V8.2 of National Instruments Corporation. Through this configuration, it is aimed to understand the discharge state of exhaust gas when the engine stop/restart and the characteristics of the engine control strategy in Hybrid powertrain.

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2. TEST EQUIPMENT AND METHOD

2.1 Test Equipment Faculty

In this study, there are two important experimental set-ups. The first parts are Hybrid powertrain composed with gasoline engine, brushless DC (BLDC) motor/generator, continuous variable transmission (CVT) and two AC dynamometers which could control the real road load and drive a scheduled mode such as Federal Test Procedure-72 (FTP-72) or New European Driving Control (NEDC). Other one are systems for measurement and analysis

2.1.1 Hybrid Powertrain and Dynamometer System

The specifications of the Hybrid powertrain are described in Table 1. This HEV system is of parallel flywheel motor/generation type using two power sources. The engine employs a 1399 cc, in-line 4 cylinder applied continuous variable valve timing just in the intake valve. As the electrical power sources for power assistance a 12 kW BLDC motor/generator and lithium polymer battery (LiPB) with nominal output voltage of 144 V are applied. Instead of using a conventional starter motor for engine start-up, the BLDC motor accomplishes this role. There are also 3 modes.

Normal mode: Engine only without motor assist

Hybrid mode: Power assistance or regeneration by motor /generator as well as engine power

Idle stop mode: Engine stop function during vehicle stop

Table 1. Hybrid powertrain specifications

Descriptions	Specification
Engine	Gasoline, 1399 cc 123 Nm/4300 rpm
Transmission	CVT
Motor/Generator	BLDC 12 kW, 90 Nm/1200 rpm
Battery	144 V, 6.5 Ah LiPB

There are two AC 300 kW dynamometers (Meiden Ltd., Japan) that can test front engine front driving (FF) or front engine rear driving (FR) type vehicles and control vehicle speed, drive shaft torque and road load. They are connected to the drive shaft at both sides instead of to the tires. Their system schematic and picture are shown in Fig.1. There are also 5 coolant temperature controllers such as engine coolant, engine oil, transmission oil, motor and fuel. Additional equipments are the follow-digital power meter (Yokogawa Ltd., WT 1600) for measuring battery voltage and current, the fuel consumption meter (Onosokky, FX1100). An torque transducer was installed specially between the engine and the motor/generator for cycle by cycle and cylinder to cylinder observation of engine out torque. The splinted flange and spacer were fabricated that accept the motor and CVT on one side and fit into the engine damper on the opposite side.

2.1.2 System Development for Combustion Stability Characteristics Analysis

The overall analysis system specified and developed for the combustion stability were composed with PXI-8196 and LabVIEW V8.2 graphic user interface (GUI) language. They are composed of 24 analogues, 96 digitals, 8 temperatures, 2 CAN channels. Four cylinder pressures were recorded using Kistler 6051 A piezo-electric pressure transducer with spark plug adaptor and Kistler 5016 A charge amplifier. In case of engine out THC measurement, the FFID analyzer (Cambustion Ltd., HFR 500) with two sampling channels, which readily achieved a response time of less than 10 ms, was utilized. It was installed as close as possible not only to the exhaust manifold (Tailpipe, front of 3-way catalyst) where the exhaust gas is collected but also to the number one cycle exhaust valve. Finally the signal condition analogue circuit was configured to determine injection and ignition timing.

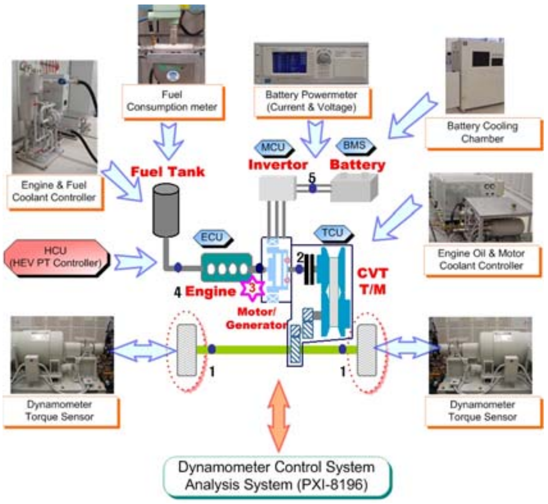

Fig. 1. Schematic diagram of dynamometer system

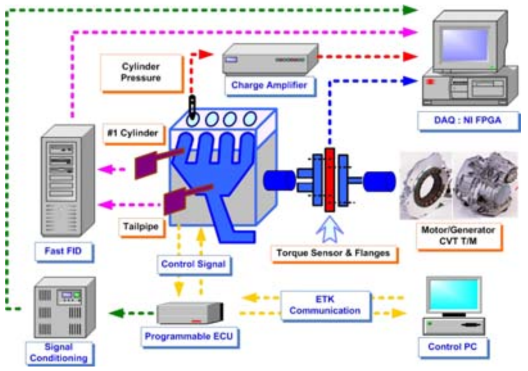

Fig. 2. Schematic diagram of the analysis system

2.2 Test Method and Procedure

For the frequent engine stop/restart generation, the par segment of phase 2 (690 ~ 1040 second, engine restart and deceleration section) in the FTP-72 driving cycle was chosen

(Fig.3). The temperature of the test room was 29 ℃. The preheated engine condition with coolant (85 ℃) and CVT oil (75 ℃) were commonly applied. The executed test condition were battery SoC, spark ignition timing and injection rate. In case of spark ignition timing, the advanced (ADV) and retarded (RD) timing between 3 and 7 crank angle (CA) which are referred to the end of compression process, namely top dead center (TDC) position of piston, were made an attempt. The injection rate was also defined according to the injection duration due to proportional relation between two parameters. Since the injection duration could be set as a map data according to the engine load, the conventional injection duration map was assumed to be x1.0 scale. If the setting value is x1.2 scale, it means 1.2 times more than conventional its map.

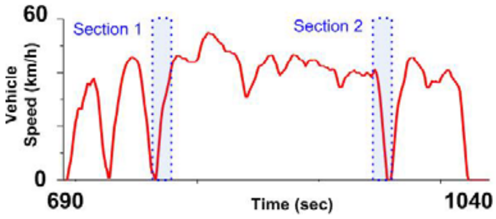

Fig. 3. FTP-72 driving mode:690~1040 second

Table 2. Test conditions

Control variables	Setting value
Batter SoC (%)	35, 55
Ignition Timing (CA)	ADV 3 & 7, TDC, RD 3& 7
Injection Rate (Scale)	x0.8, x1.0, x1.2, x1.5

3. EXPERIMENTAL OBSERVATIONS AND RESULTS

3.1 Injector Characteristics and Phenomena Observation at Engine Restart State

3.1.1 Prediction of Injection Rate for Each Cycle Process

For prediction of injection rate for each cycle process, injector characteristic experiment was attempted in not extra injector rig test but engine operating state. As you know, the injection rate will be defined with 3 parameters which are injection duration, rail pressure and 12 V battery voltages (1). However, in this study, the injection duration was only selected as a parameter which determines the injection rate due to the largest interrelation among them (2). In constant engine and vehicle speed state, the fuel consumption was measured by weight type fuel consumption meter. After that, the mean fuel consumption per cycle was calculated. The rail pressure is 3.2 bar and the 12 V battery voltage is 13.5 V. There is a linear interpolation formula (2) which is relation between injection duration and injection duration (Fig.4). In engine idle state, the injection duration is 2.7~3 ms and it is equal to about 0.05 g/cycle.

$$\begin{aligned} &F_{INJ} = f(t, P, V) \\ &F_{INJ} : \text{Injectionrate, } g / \text{cycle} \\ &t : \text{Injection duration, ms} \\ &P : \text{Rail pressure, bar} \\ &V : \text{12 V Battery voltage, V} \end{aligned} \tag{1}$$

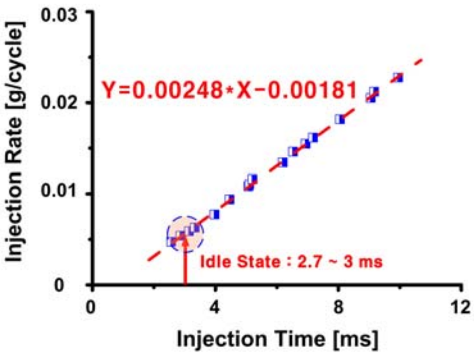

Fig. 4. Injector test for relation between injection duration and injection duration

$$F_{INJ} = 0.00248 \times t - 0.00181 \tag{2}$$

3.1.2 Engine Restart Characteristics

The combustion characteristics will be compared at the instantaneous engine restart process after idle stop where the initial battery SoC conditions are 35 and 55 % conditions. In engine speed and battery current graph (Fig.5), the engine restart step is two cycle (0~1440 CA) using motor and the next one cycle (1440~2160 CA) is the process reached at engine idle speed by engine combustion, not motor. In this case, one cycle amounts to 720 CA and the 4 stroke was defined through each 180 CA such as intake, compress, expansion, exhaust process. A reason why the engine speed is about 500 rpm at the first cycle (0~720 CA) is that the data acquisition starts with encoder trigger signal for the TDC position synchronizing and IMEP calculation. Therefore there is a time difference between engine start and data acquisition less than one cycle. In the first cycle (0~720 CA) of the engine speed graph, there is just the spark ignition signal. It means the engine state cranked by motor. After that cycle, the first injection is occurred around engine speed 1100 rpm. In case of the conventional gasoline engine operated by starter motor, the first injection could be observed between 200 and 300 rpm of engine speed and then the engine speed reached at idle speed 800~850 rpm. Hence it could cause vibration or noise due to variation of output power by a steep combustion. But these problems could be come down in the hybrid electric vehicle since the steady power is produced by motor and the combustion begins after reaching at idle speed. Furthermore, it makes profitable combustion due to high pressure and temperature air condition in the cylinder.

In the THC trend graph and the end of the 3rd cycle (1440~2160 CA), the THC abruptly increased both cylinder 1 and tailpipe. It could be explained that the unburned hydrocarbon was exhausted directly as a result of misfire or partial burning. After the unstable combustion, the THC was decreased at exhaust valve open (EVO) timing which is the end of the 4th cycle (2160~2880 CA). It could be considered as a stable combustion from the 4th cycle.

Using the conventional control setting value, the spark ignition timing is retarded 5 CA and the injection rate is zero due to engine motored state in the first cycle (0~720 CA). Next 2nd cycle (720~1440 CA), fuel injection was started, after that, the misfire or partial burning was occurred in the 3rd cycle (1440~2160 CA). At that time, the spark ignition timing is advance 10 CA referred to TDC position and the injection duration is 6 ms. However, the combustion is well for 5~6 cycles despite less than 6 ms and the result can also be compared to 2.7~3 ms for idle engine state. The specified analysis will be followed in a next paragraph.

Through this engine restart characteristics observation, three test conditions were decided; battery Soc, spark ignition timing, injection rate.

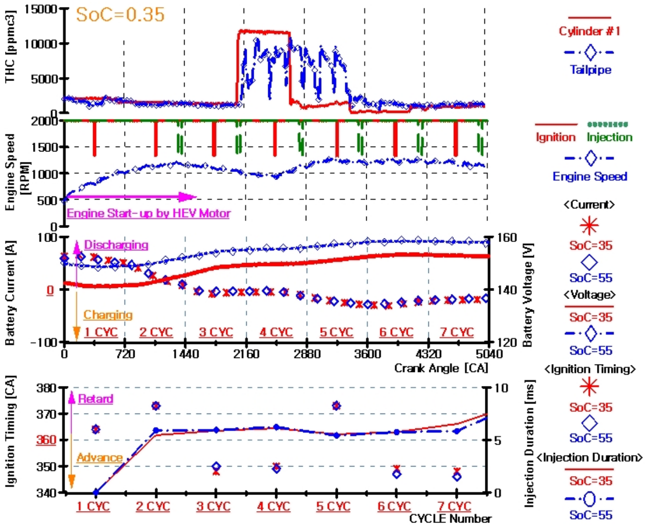

Fig.5. THC emission and engine control at SoC 35, 55 %

3.2 Combustion Stability Characteristics with the Control Variable Conditions

3.2.1 THC emission characteristics with the battery SoC Conditions

The experiment was leaded from the concept that the battery SoC difference could affect the engine restart characteristics. However, not only the engine out THC emission trend but also spark ignition timing and injection rate are so similar both SoC 35 % and 55 % like as the results in the Fig. (5) regardless of the battery SoC. The transferred power from battery/motor to engine is equal to 9.5 kW. There are just tiny differences in the battery voltage and current. Compared SoC 55% to the SoC 35 %, the current is less than 3~4 A and the voltage is more than 5~7 V. Although it could be inferred that the energy loss induced by the internal resistance is decreased in case of the high battery SoC state, the effect will be limited. Therefore the battery SoC difference could be considered negligible parameter.

3.2.2 THC emission characteristics during deceleration state

During deceleration driving of the hybrid powertrain, the engine is motored with fuel cut function which is defined as no longer injection signal; after the 4th cycle (3520~4320 CA) in Fig.6 A significant amount of THC emission is observed after the 4th cycle and then the injection duration is less than 2ms. One of reason why the THC emission were abruptly increased in the end of 4th and 5th cycle was caused by the unstable combustion of fuel which was injected at the end of 3rd and 4th cycle with a retarded spark ignition timing. When the injector response time and injection duration (2.7~3 ms) were considered, a critical factor is not the injected fuel but discharging by the fuel piled up intake manifold, intake valve, piston and crevice volume. During the engine motored cycle, the deposited fuel was vaporized and purged to the tailpipe. Hence, along the arrange driving, not only the residual fuel but also the amount of THC emission will be decreased. In the middle of 5th and 6th cycle or 6th and 7th cycle, the cave shape like as a hollow pool was observed because of the reverse flow from THC sampling probe to cylinder at the exhaust valve open (EVO) timing due to pressure difference. In order words, it could be assumed that the intake pressure in intake valve open (IVO) and exhaust pressure in EVO was same and then the intake pressure was 0.4 bar and the sampling pressure was 0.55 bar. Hence the reverse flow is possible.

3.2.3 THC emission characteristics in the front and rear of 3-way catalyst

As you know, the amount of THC emission could be diminished using the 3-way catalyst. Although its conversion efficiency is quite high, however, it could not exactly block them if the amount of THC emission were produced due to misfire or partial burning. In this case, the relation between 3 way catalyst and THC emission according to the catalyst temperature was investigated during engine restart and

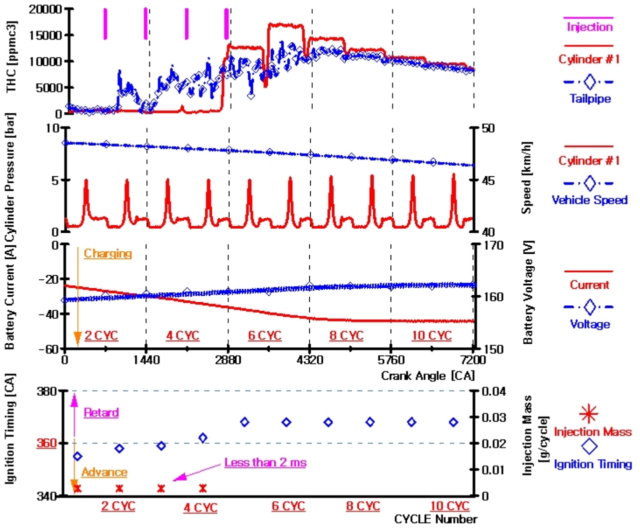

Fig.6. THC emission and engine control during deceleration

deceleration driving. The FFID sampling probes were installed both the front and the rear of tailpipe merged with the 4 exhaust pipes.

Before the engine restart experiment, the down time is about 20 second from idle stop to engine restart. The catalyst temperature was about 300 ℃ at engine restart. The THC scale difference is one of ten in Fig. (7). After the front THC emission increases at the end of the 3rd cycle (1440~2160 CA), the increasing of the rear one is indicated with 1 cycle delayed. In the case of the IMEP and injection signal, the 1st and 2nd cycles are engine motored cycle and the IMEP value are near zero. In the 3rd cycle (1440~2160 CA), however, the calculated IMEP stand for the three abnormal combustion cylinders and only one well. The efficiency of the catalyst is around 90 %.

In case of the deceleration test in Fig. (8), the catalyst temperature is about 600 ℃. Although the engine out THC emission trend is as similar as that of the engine restart test, the THC emission after the catalyst is very small. Its efficiency is around 99 % and it could be decided as a high temperature of the catalyst. But there is a hidden fact. The amount of THC emission is mole fraction, not mass. Hence, even if the mole fractions are equal, the trend whether the THC emission is small or not after the catalyst could be incorrectly analysis. At now, the experiments according to the catalyst temperature are going.

Anyway, it could be concluded that the low catalyst temperature will cause more and more THC emission if the down time is sustained for a long time.

3.2.4 THC emission characteristics with the spark ignition timing and injection duration

Until now, the THC emission characteristics were investigated during engine restart and deceleration driving. In this section, the way how can get the stable combustion will be explained.

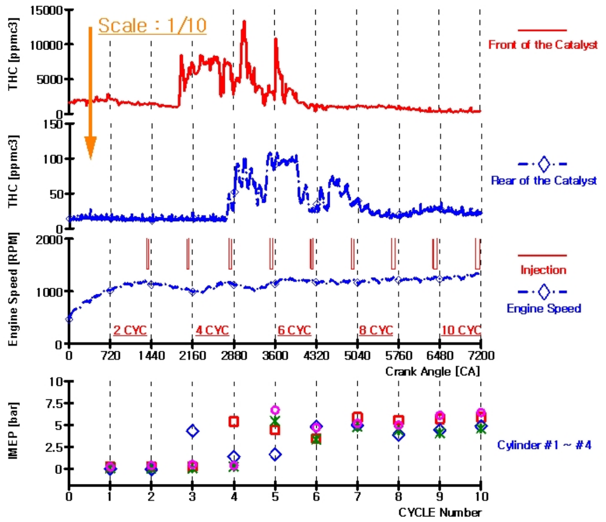

Fig.7. THC emission in the front and rear of the 3-way catalyst during engine restart

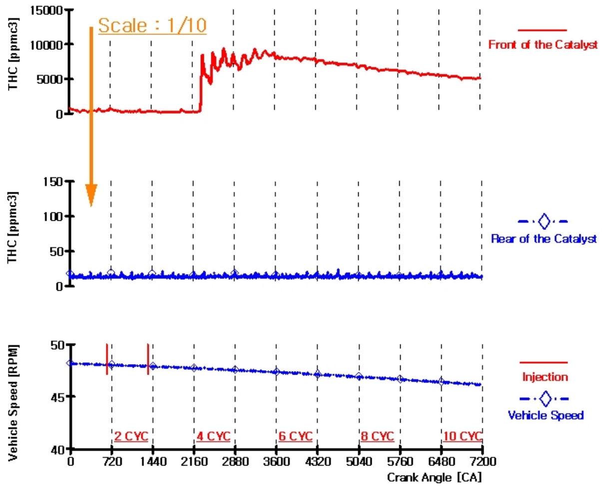

Fig.8. THC emission in the front and rear of the 3-way catalyst during deceleration

From the earlier results in Fig. (5) if the conventional engine control map was applied, it could be concluded that the misfire or partial burning will be always occurred after the 1st injection in the process of engine restart. At this point, the spark ignition timing is advanced crank angle and the injection duration is 6 ms. Referred to the results, the spark ignition timing was set from ADV 7 to RD 7 and the injection duration was set from x0.8 to x1.5 in Fig. (9). The conventional injection duration map was assumed to be x1.0 scale. If the setting value is x1.2 scale, it means 1.2 times more than conventional its map. Seven number of the upper side at each graph in Fig. (9) stand for the injection duration matched with each cycle. Regardless of the spark ignition timing, the misfire and partial burning were occurred at x1.0 and x0.8 and the stable combustion were observed at x1.2

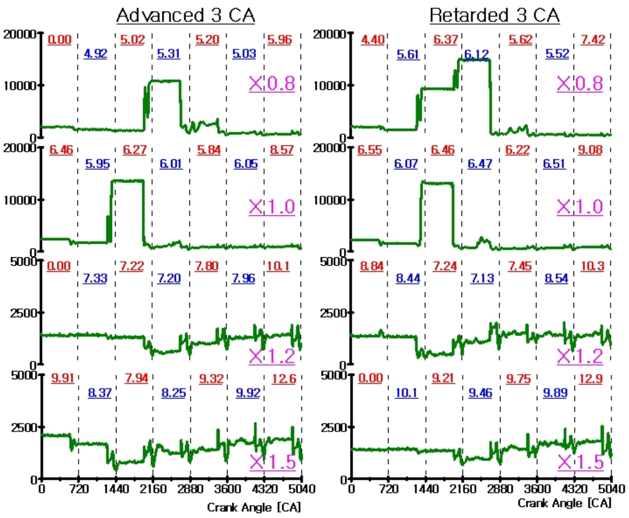

Fig.9. THC emission and engine control results

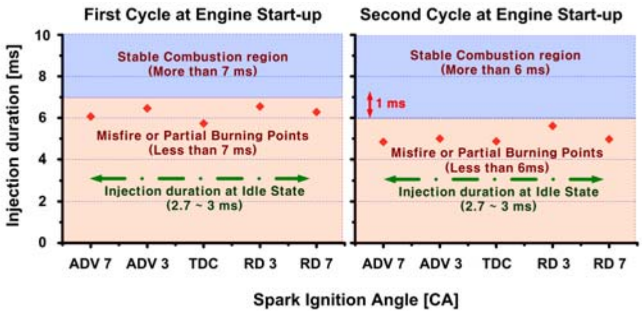

Fig.10. Relation of spark ignition timing and injection duration

and x1.5 due to more fuel injection. In case of the spark ignition is retarded 3 CA and the injection duration is x0.8, there were continuous abnormal combustion. In the injection for the next cycle after the abruptly THC emission increasing at x0.8, the injection duration were 5.02 ms (1440~2160 CA) for ADV 3 CA and 5.61 ms (1440~2160 CA) for RD 3CA. Although more fuel was injected in case of RD 3 CA compared to the ADV 3 CA, there was so incomplete combustion due to the low temperature and pressure according to the retarded spark ignition timing. Other test results with the spark ignition timing change had also so similar. However the injection duration which is more than x1.2 leaded to a good combustion regardless of the spark ignition timing. From the results, the range map both the spark ignition and the injection duration could be derived in Fig.(10) during the first and second cycle shortly after the engine start-up. For the stable combustion, the limit of the injection duration is 7ms at the first cycle and 6 ms at next cycle. At this point, although the injection duration of the engine idle state is 2.7~3 ms, the combustion is quite good. However the results showed incomplete combustion despite of two times more than general idle state for the injection duration. It could be explained the previous research of Nagaoka et al. He said that the injected fuel from injector was 50 % and the deposited fuel from intake port, valve, piston and crevice volume was 50 % if the fuel used for combustion was100 %. Since the deposited fuel was vaporized and exhausted during the deceleration driving, the residual fuel was dismissed and more fuel injection was needed for a stable engine start-up.

4. CONCLUSIONS

Using hybrid powertrain, FFID and analysis tools, the engine control and THC emission characteristics were investigated according to the spark ignition timing, the injection duration and battery SoC.

When the conventional engine control map was applied, the spark ignition timing is advanced 10 CA and the injection duration is 10 ms at the first cycle after the engine start-up.

The effect of battery SoC was so tiny and the assist power was 9.5 kW. During the deceleration driving, the fuel was blocked and the THC was abruptly increased due to the deposited fuel at the intake port, piston and crevice volume.

Although the efficiency of 3 way catalyst was more than 90 %, amount of THC emission were indicated at the rear of catalyst during the abnormal combustion.

Finally, the more fuel injection was lead to the better combustion; the quantity was 1.2 times more than the conventional injection duration however the effect of the spark ignition timing change was so small

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